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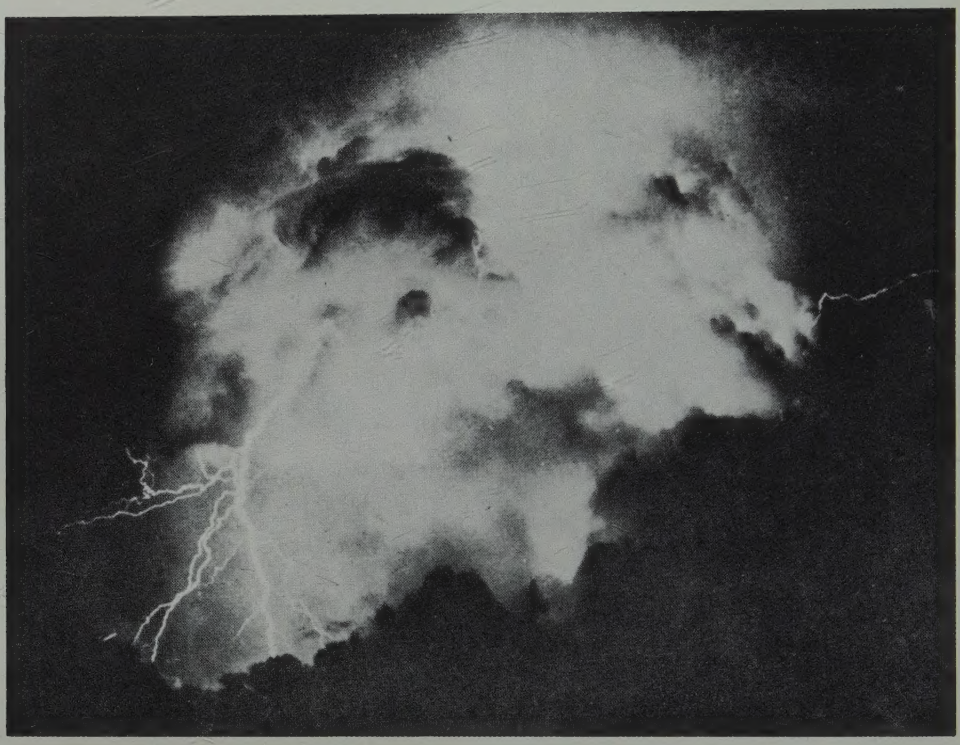

STORM OVER SINGAPORE
(Photograph by Major R. Thomas)

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RAINFALL OF SINGAPORE ISLAND

By

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INTRODUCTION

Although there is no accepted international standard for the spacing of rain-gauges in a climatological network, it is usual to describe the mean rainfall of a comparatively level area the size of Singapore (about 170 square miles) by the records of a single gauge[1]. The adequacy of such a description is tested in this investigation, and a variation of monthly and annual mean rainfall with locality is sought. For this purpose a large number of rain gauges was maintained on the Island during 1953[2]. The records of these gauges, together with those of past years, are used in investigating the following five related problems.

(1) What are the mean monthly and mean annual values of rainfall over the Island, and how does the wind regime influence the seasonal variation?

(2) What is the geographical distribution of rainfall over the Island?

(3) Is the diurnal variation of rainfall the same at all seasons and in different parts of the Island?

(4) Of what size, duration and movement are the individual storms, and how representative are the observations of a single rain-gauge?

(5) Does such a condition as "general rain" exist, and is the boundary between two air-streams accompanied by a rain-band or by separate rain-storms ?

Because little has been written previously concerning the rainfall of Singapore, many of the references herein are to work on similar problems elsewhere Those quoted in the formulation of the problem (in Chapter I) fall into fou categories:

(1) Those dealing with conditions at Singapore.

(2) Those dealing with similar problems in the East Indies where the atmosphere, like that above Singapore[3], is generally conditionally unstable[4].

(3) Those dealing with conditions in the tropics remote from the Equator where there is normally a "Trade-wind Inversion"[5]. References in this category have been treated with reserve as the atmospheric structure aloft is unlike that over Singapore.

(4) Those dealing with conditions outside the tropics. Works cited in this category are only those concerned with the rainfall of thunderstorms in the United States during summer, as the air is then usually conditionally unstable[6]. The justification for this inclusion is that the heavier falls at Singapore, which contribute so much to the monthly precipitation totals, invariably occur in thunderstorms. Thus in 1953 (i) Kallang Airport reported 200 days with thunderstorms; (ii) of the eight occasions when rainfall intensity at Kallang exceeded one inch per hour, seven were in thunderstorms; and (iii) on both of the occasions when rainfall exceeded two inches per hour there were thunderstorms.

1. e.g, *Weather Guide for Long Range Planning, Singapore, Straits Settlements* (U.S. Weather Bureau, 1944), p. 2.
2. The distribution of these gauges is described in Chapter II.
3. I. G. John, *The Properties of the Upper Air Over Singapore: Memoirs of the Malayan Meteorological Service, No.* 4 (Singapore, 1950), p. 13.
4. N. Shaw, *Manual of Meteorology*: Vol. 3, *The Physical Processes of Weather* (London, 1939), p. 286.
5. H. V. Ficker, *Die Passatinversion* (Berlin, 1936).
6. *The Thunderstorm: Report of the Thunderstorm Project* (Washington, D.C., 1919), p. 20.

CHAPTER I.

REVIEW OF PREVIOUS WORK AND FORMULATION OF THE PROBLEM

(1) MEAN VALUES AND SEASONAL VARIATION

The history of rainfall reporting in Singapore is given as follows in a United States Weather Bureau publication[1]. The British East India Company maintained an observatory at Singapore early in the nineteenth century, and published observations were available from 1841 to 1845. These records, however, were made prior to the standardization of observations by the International Meteorological Committee (1872) and, since there was some question as to their accuracy, they were not included in the *Guide*. Government records began in 1878 and, except for a few breaks, were available until 1916. From 1917 to 1938 monthly summaries were available. Observations were made at Kandang Kerbau Hospital[2] from 1878 to 1929, at Mount Faber from 1930 to May 1934, and at Kallang Airport from June 1934 to 1941.

Using all available observations after 1877, the United States Weather Bureau prepared diagrams showing the probability of precipitation in various months. Table 1 and Fig. 1 are abstracted from that paper[3] with the permission of the Chief of the United States Weather Bureau. Fig. 2 (from the same source) gives mean and extreme values of monthly rainfall.

A description of the rainfall of Singapore is also supplied by the Far East Air Force in *Notes on Weather Conditions in India and the Far East,* where it is stated that Singapore has a fairly uniform climate with small seasonal variations[4]. Average rainfall (inches) at Singapore is given as:

J	F	M	A	M	J	J	A	S	O	N	D	YEAR
9.9	6.9	7.6	7.4	6.9	6.8	6.7	7.6	7.0	8.2	10.0	10.2	95.2

Rainfall means differing slightly from both the Far East Air Force values and those of the U.S. Weather Bureau are given by the Australian Meteorological Branch[5], which provides the following statistics for Singapore (falls in inches):

	J	F	M	A	M	J	J	A	S	O	N	D	YEAR
MEAN MONTHLY	9.88	6.85	7.64	7.40	6.81	6.77	6.65	7.68	7.01	8.19	9.96	10.16	95.00
MEAN HIGHEST DAILY[6]	8.59	5.55	6.62	5.31	8.46	3.94	7.24	4.17	3.94	6.02	7.24	9.29	9.29
RAIN DAYS	17	11	14	15	15	13	13	14	14	16	18	19	17.9

1. *Weather Guide for Long Range Planning, Singapore, Straits Settlements.*
2. Recolds of the *Malayan Meteorological Service* show that Kandang Kerbau observations commenced in 1875 and that Mount Faber observations were made until the end of 1929.
3. *Weather Guide for Long Range Planning*, pp. 3, 4.
4. *Notes on Weather Conditions in India and the Far East*: Meteorological Branch, Air Command, Far East Air Force, 1947), pp. 1-41.
5. *Rainfall Data for the East Indies (Excluding Sumatra). Australian Met. Branch Report List No. 3*, Sect. 2, Series 7, No. 21 (1945).
6. This is apparently an error and refers to absolute maximum daily falls.

TABLE I. SINGAPORE PRECIPITATION SEQUENCE AND PERSISTENCY.

	MONTH	SEQUENCES NUMBER OF PERIODS[1]			MAXIMUM PERSISTENCY DURATION, IN DAYS, OF PERIODS		
		<0·01 IN.	0·01 IN. OR MORE	0·40 IN. OR MORE	<0·01 IN.	0·01 IN. OR MORE	0·40 IN. OR MORE
LEAST	JAN.	3	2	1	2	2	1
	FEB.	2	1	0	2	1	0
	MAR.	2	2	0	2	1	0
	APR.	3	3	2	2	2	1
	MAY	4	3	1	2	1	1
	JUN.	5	4	2	2	2	1
	JUL.	3	4	0	2	2	0
	AUG.	4	5	0	2	1	0
	SEP.	3	2	1	1	2	1
	OCT.	3	4	1	2	2	1
	NOV.	3	3	2	2	2	1
	DEC.	2	2	2	1	3	1
MOST LIKELY	JAN.	5-6	5-7	4-6	3-5	4-7	2-3
	FEB.	5-6	4-6	1-4	4-9	2-4	1-2
	MAR.	4-6	5-7	2-4	3-7	2-5	1-2
	APR.	6-8	6-8	4-5	4-5	3-5	1-2
	MAY	6-8	5-7	3-4	4-6	3-5	1-2
	JUN.	6-7	5-6	4-5	4-7	4-5	2-2
	JUL.	6-7	6-7	4-5	4-6	3-5	1-2
	AUG.	6-8	5-7	4-6	4-6	4-7	1-2
	SEP.	6-7	6-7	3-4	4-6	4-7	1-2
	OCT.	6-8	6-7	3-5	3-6	3-5	1-2
	NOV.	6-7	5-7	4-6	3-4	4-7	2-3
	DEC.	7-8	6-8	5-7	2-3	5-7	2-3
GREATEST	JAN.	10	10	8	13	24	7
	FEB.	7	7	6	26	12	5
	MAR.	10	11	10	30	16	4
	APR.	9	9	8	16	14	5
	MAY	10	10	7	13	10	5
	JUN.	9	10	7	11	12	4
	JUL.	9	9	8	17	12	4
	AUG.	10	10	10	12	14	4
	SEP.	9	9	7	12	11	4
	OCT.	10	10	9	12	9	4
	NOV.	10	10	8	8	15	6
	DEC.	9	10	10	12	23	7

1. For the purpose of this analysis a period is one day or a number of consecutive days. For a note on the data in this table see the caption to Fig. 1.

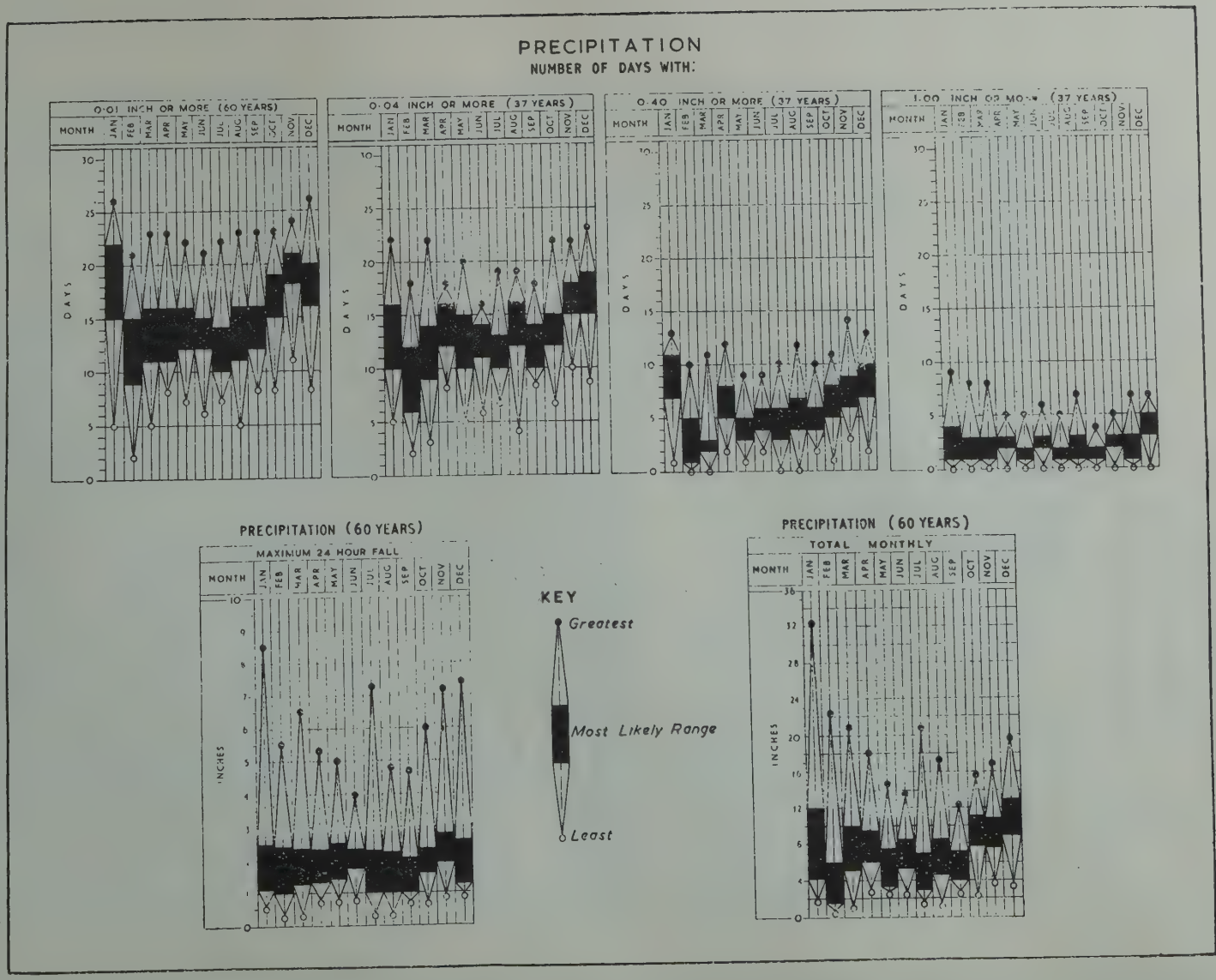

Fig. 1. Singapore: precipitation expectancy. The data shown as MOST LIKELY are the limits bracketing the smallest range which includes at least 50 per cent of the events in the period of record. The MOST LIKELY is used here, because the "average" (or mean value) occurs frequently only in a reasonably symmetrical distribution when it then lies approximately half way between the limits of the MOST LIKELY. When the distribution is not symmetrical, the limits of MOST LIKELY do not necessarily include the average (or arithmetic mean), but do include the values that have occured with the greatest frequency. A rough picture of the expectancy curve can be obtained by considering the shapes of the triangles on either side of the MOST LIKELY rectangle. Redrawn from *Weather Guide for Long Range Planning: Singapore, Straits Settlements* (United States Weather Bureau, 1944), p. 3.

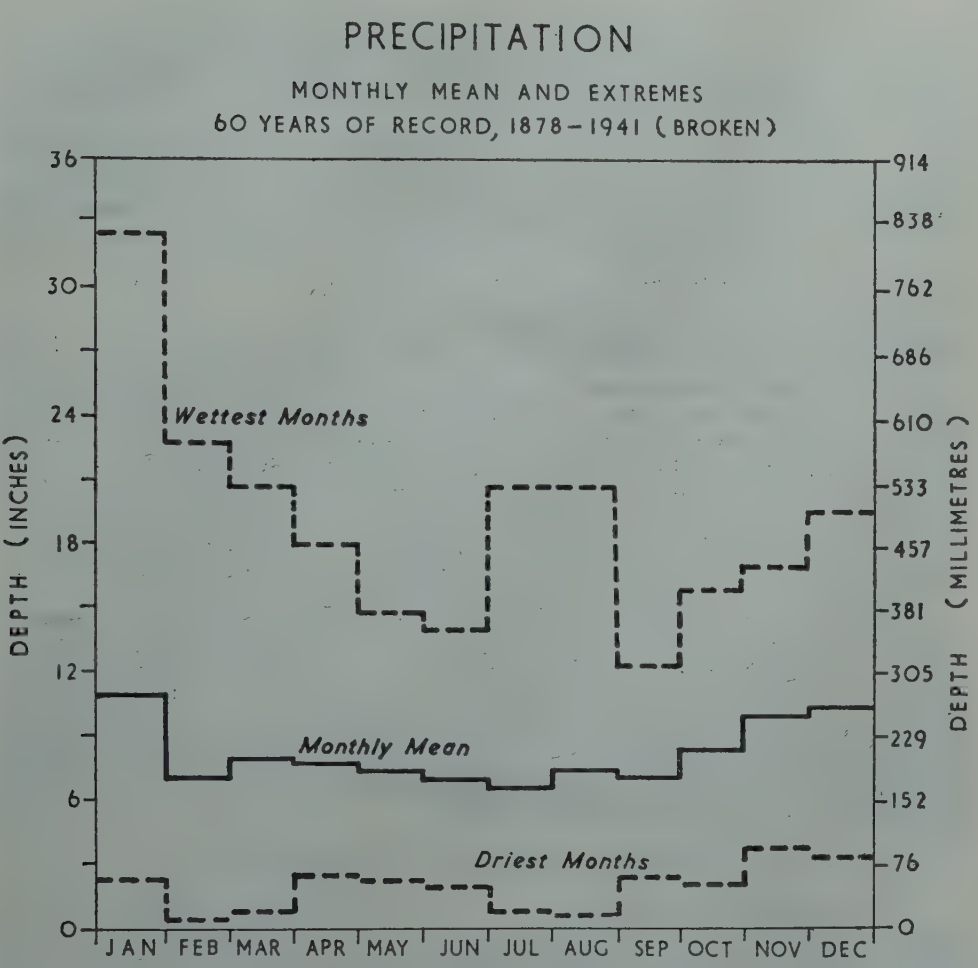

Fig. 2. Singapore: monthly mean and extremes of precipitation. Reproduced from *Weather Guide for Long Range Planning: Singapore, Straits Settlements*, p. 4.

Still another series of means for Singapore is supplied by Stewart[1] as follows:

	J	F	M	A	M	J	J	A	S	O	N	D	YEAR
RAINFALL (IN.)	9.88	6.62	7.40	7.64	6.65	6.85	6.77	7.95	6.77	8.07	9.92	10.55	95.07

The discrepancies in the published mean monthly and mean annual values may indicate that the means cover different periods or, in view of the history of rainfall reporting in Singapore, that they refer to different sites. Leopold[2] has shown that in the Hawaiian Group, where there is little seasonal variation of

1. C.D. Stewart, "Rainfall of Malaya", *Malayan Agricultural Journal*, Vol. 18, No. 11 (Kuala Lumpur 1930), p. 533.

2. L.B. Leopold, "The Annual Rainfall of East Maui", Second Issue of the *Hawaiian Planters' Record* (Hawaiian Sugar Planters' Association, Honolulu, 1949), pp. 47-63.

upper-wind, mean annual precipitation varies with exposure. This raises the question as to whether the published mean values for a single station on Singapore Island, where there is considerable variation in upper-winds, could adequately describe precipitation over the whole Island.

Published mean monthly values of rainfall show a seasonal variation. The Far East Air Force publication lists the seasons of South-East Asia as follows:[1]

(i) The North-East Monsoon (Dec.-Feb.) when north-easterlies, flowing out from the Asiatic High cover the area.

(ii) The pre-monsoon transition period (Mar-May).

(iii) The South-West Monsoon (June-Sept.).

(iv) The post-monsoon transition period (Oct.-Nov.).

Stewart also has discussed the seasons[2]. In his account of the seasonal variation of rainfall over Malaya (including Singapore), he recognizes three rainfall regions: a West Coast Region, an Inland Region, and an East Coast Region, in which Singapore is included. The seasonal variation is described as due to the changes in the main wind currents. The North-East Monsoon starts in late October or during November and continues until March. The South-West Monsoon is aloft from May to August, but the prevailing low-level winds are then south-easterlies. Each of the intermonsoon periods lasts eight weeks.

Over the East Coast Region the rainfall follows the North-East Monsoon, reaching its maximum intensity about the middle of the monsoon in December, and its minimum in July. The seasonal variation is small at Singapore, which has the lowest wet-season rainfall and the highest dry-season rainfall of the East Coast group. Seasonal percentages of annual rainfall are: Nov.-Feb. 41; Mar.-Apr. and Sep.-Oct. 30; May-Aug. 29. As there are differences in these two descriptions of the seasons, the relation of the seasonal variation of rainfall to winds over Singapore is examined in the present paper.

(2) GEOGRAPHICAL DISTRIBUTION OF RAINFALL

The differences between the various published values of mean rainfall at Singapore could possibly be explained by different observing sites, so that the present study includes a search for any variation of rainfall with locality. The long-period mean monthly and mean annual isohyetal maps prepared for this purpose cover only a limited portion of the Island, but a denser observing network was established in 1953 to study the detailed isohyetal patterns over one complete year. H. J. de Boer[3] has made similar studies in Java, where it was found that the variation of annual rainfall with locality depended on the wind-streams and topography. There was a rainfall maximum at 1,200 metres over West Java, while totals decreased towards the plains and diminished rapidly towards the coasts. Central and East Java each showed two maxima at 1,200 and 800 metres, and thence rainfall decreased both towards the summits of the mountains and towards the plains.

The highest point on Singapore Island, however, is only 481 ft., and an investigation of the relation of rainfall to topography has not been included in the present study.

1. *Notes on Weather Conditions in India and the Far East.* pp. 3-4.

2. Stewart, op. cit, pp. 530-40.

3. H.J. de Boer, "On the Relation between Rainfall and Altitude in Java, Indonesia", *Chronica Naturae*, No. 106, Vols. 8-9 (Bandoeng, 1950), pp. 424-7.

(3) DIURNAL VARIATION OF PRECIPITATION

It is stated by Far East Air Force that there is a definite diurnal variation at Singapore with rain occurring mostly in the afternoon or early evening[1]. Cook found a similar variation at Denver, Colorado, where from recordings of a single gauge, highest frequencies and greatest amounts of summer rainfall were found to be in the afternoon and early evening, with negligible amounts between midnight and noon[2]. There was a close correlation between diurnal thunderstorm variation and daily rainfall variation at Denver so that thunderstorms were the prime factor in summer rainfall distribution.

Contrary to these findings, curves prepared by Lea show that highest frequencies at Singapore are in the early morning during some months[3]. This suggests that the problem should be investigated further. The present investigation therefore includes a search for differences in diurnal variation according to locality, because this could explain the differences in opinion concerning the diurnal variation at Singapore. This supposition is encouraged by Leopold's finding that there are different diurnal sequences in different parts of the Hawaiian Group[4]. Leopold found that orographic precipitation in the Trades occurred mostly at night (e.g., the diurnal variation of precipitation at Hilo), and the effect might extend to leeward of the ranges (e.g., diurnal variation of precipitation at Honolulu). The effect was not marked at Lanai (e.g. diurnal variation of precipitation at a station in the centre of Lanai), which was sheltered from the Trades by being in the shadow of the higher island of Maui. Leopold discusses Loveridge's thesis that nocturnal rainfall at Hawaii was due to radiative cooling at the tops of the clouds[5]. Such a diurnal variation of temperature aloft at all levels was found at Honolulu, but at some distance from the hill crests. Cooling at all levels meant a lowered condensation level, which had in fact been observed. Furthermore, wind-speeds aloft were stronger at night, which would mean more turbulence and increased drop-size. In Honolulu city many rain-showers resulted from droplets blown considerably to leeward of the cloud producing them. Convective showers were important on leeward drier areas, when only a moderate part of the moisture had been dropped in prior orographic lifting (e.g., diurnal variation of rainfall at Leilehua on Oahu).

The necessity arose during the present study of including an examination of the diurnal variation of rainfall offshore from Singapore. Braak[6] has previously found that maximum precipitation at Discovery Oostbank (a reef between Billiton and Borneo) occurred between 5 a.m. and 2 p.m.

(4) THE FORM AND MOVEMENT OF STORMS

Early in the present investigation it was realized that even heavy rain over Singapore is frequently quite local in character. This raises the question as to whether any single observation of rainfall is representative of the surrounding area

1. *Notes on Weather Conditions in India and the Far East*, p. 15.
2. A.W. Cook, "The Diurnal Variation of Summer Rainfall at Denver, Colo." *Monthly Weather Review*, Vol. 67, No. 4 (Washington, D.C.,) pp. 95-98.
3. C.A. Lea, Unpublished data on the diurnal variation of rainfall at Singapore, *Malayan Met. Service Library* (Singapore, 1950).
4. L.B. Leopold, "Diurnal Weather Patterns on Oahu and Lanai, Hawaii," *Pacific Science*, Vol. 11, No. 2 (Hawaii, 1949), pp. 81-87.
5. E.H. Loveridge, "Diurnal Variation of Precipitation at Honolulu," *Monthly Weather Review*, No. 52 (Washington, D.C., 1924).
6. C. Braak, "Diurnal Variation of Rainfall at Sea," *Het Klimaat van Nederlandsch-Indie*, Deel 1, Aflevering 8 (Batavia, 1925), p. 255.

and whether a form of 'frontal' or 'airstream' synoptic weather-analysis is permissible. To decide these points and to obtain a synthetic picture of mean monthly rainfall over the Island, a large portion of this study has been devoted to the examination of isohyetal patterns associated with individual storms.

Similar studies have been conducted elsewhere. Boerema[1] investigated the development of showers by means of 10 recording gauges within 130 sq. kilometres (50 sq. miles) near Batavia during 23 consecutive months. Of 523 showers in twelve months, less than one-tenth extended over all stations; about one-quarter extended over the four central stations of the network. It was found that the maximum intensity of a shower was not simultaneous at all stations, nor were highest intensities or total amounts equal. Boerema considered that the absolute maxima at the ten stations were probably the same because, even in the whole Archipelago, the maximum rainfall over one hour or less varied only slightly.

Brancato[2] combined an investigation of rainfall intensities at Sevier Basin, Utah, with a study of the speed of travel and area of storms at Muskingum River Watershed, Ohio; half-hourly isohyetal maps were used. In July and August nearly all rainfall amounts of 0·25 in. or more over Sevier Basin, Utah, were associated with thunderstorms. The travel of most storms depended on the 4,000 to 6,000-ft. winds but, while the individual storms moved down-wind, propagation of new storms was along convergence zones which usually lay across-wind[3]. If the wind was less than 10 m.p.h. thunderstorm movement was in any direction and sometimes up-wind. The average width of the rainfall was found to be 6 miles[4], with extremes varying from a few miles to 12 miles, and most thunderstorms reached maximum intensity within one hour of the beginning of rain.

It is stated that the structure of a thunderstorm is rather more complex than a Benard cell[5] of which the diameter is $3\frac{1}{2}$ times the height, with upward motion at the centre, divergent at the tops and descending at the outer region. The size of the thunderstorms could depend on the height of the instability layer. Assuming instability to extend to the tropopause (9 miles in U.S. summer), the width of the cell would be 31·5 miles ($9 \times 3\frac{1}{2}$). If ascending motion in the visible portion of the cell was half the total cell, the diameter of the cloud was 16 miles. Observations had shown that rain fell from three quarters or less of the width of the cloud. This would account for a width of 12 miles, which agreed with 100 cases of maximum isohyetal patterns at Muskingum[6].

In the Muskingum experiments, the duration of flood-producing rainfall never exceeded two hours and the average was one-half to one hour. When the 6,000-ft. wind was strong, duration was short and intensity low. The short duration was due either to shearing or to a greater inflow velocity into the storm causing quicker release of latent energy, so that maximum intensity was reached more quickly. The lowered intensities were due to the great speed of travel over one place.

The United States Government has issued a comprehensive report entitled *Thunderstorm Rainfall* concerning the nature, formation and frequency of thunderstorms and their associated rainfall. The theory is built up from a very extensive

1. J. Boerema, "Uitbreiding van Regenbuieu te Batavia" *Koninklijk Magnetisch en Meteorologisch Observatorium te Batavia*, Verhandelingen No. 15 (Weltevreden, 1925), pp. 20-1.
2. G.N. Branato. *The Meteorological Behaviour and Characteristics of Thunderstorms* (Washington, D.C., 1942), pp. 1-16.
3. ibid., p. 2.
4. ibid., pp. 2-3.
5. As described in *Annalen der Physik und Chemie*, vol. 23 (Paris, 1901).
6. ibid., p. 3.

literature and relies heavily on Brancato's work. The average duration of rain at a station in the path of a storm was found to be one hour, and in the few instances where a single thunderstorm was traced from origin to dissipation across the map, the duration was two to three times as long[1]. Its path was approximately parallel to the 6,000-ft. wind and of the same speed. Close examination of the incremental isohyetal pattern for small units of time (15 minutes or less) showed that this correlation was best sustained for the general or overall speed and direction. In smaller intervals the storm as evidenced by the isohyetal pattern moved up or down or across the wind.

It was possible to calculate the amount of rainfall over an area of approximately 10,000 sq. miles and of duration of twenty-four hours or more from the precipitable-water content of the convergent layer (of individual convective cells) and of the outflow layer[2]. The rainfall thus determined was called effective precipitation, but distribution of rain within the area was not so easily determined, as complications occurred by trajectories and shear affecting raindrop size.

Brancato's estimate of a maximum isohyetal pattern of 12 miles is said to be neither an average nor limiting value of the individual thunderstorm or its rain pattern. The areal extent of individual thunderstorms was complicated by a tendency for storms to develop in groups or families, so that the very existence of individual cells could not be proved. Furthermore, the local storm with a good isohyetal pattern produced much less rain than the widespread storm. The half-hourly Muskingum isohyetal maps showed that the highest average and extreme half-hourly amounts at individual stations occurred when rain was so general that no individual cells could be determined. The short rainfall period used seemed to rule out the possibility that higher amounts could be due to the chance succession of individual cells over the same point[3].

Further studies of the rainfall associated with thunderstorms are described by the United States Department of Commerce[4]. The U.S. Air Force, the Navy, the National Committee for Aeronautics and the Weather Bureau have combined in this study. The report is comprehensive, covering the theoretical aspects of thunderstorms, their development, and the measurement of turbulence and of the electric field within the storms. Particular cases are discussed with the observations by ground radar and by aircraft flying through the storms.

It was found that the sharpness of the rain-area boundary of a storm varied as the age of the cell. Early in the mature stage, the horizontal gradient of rate of rainfall was usually steep — values of 0·60 in./5 mins./mile were observed. As the cell aged, this rainfall-intensity gradient decreased.

The duration of moderate or heavy rain from a single cell varied from a few minutes in weak, short-lived cells to almost one hour in large mature ones. The duration of the rain-period observed at a surface station depended on a number of factors since:

(i) the number, size and longevity of cells in a storm passing over a surface station determined the duration of that storm,

(ii) the duration of precipitation varied with the position of the station with regard to each passing cell,

(iii) the rate of travel was significant.

1. *Thunderstorm Rainfall: Hydrometrical Report No. 5.* (Waterways Experiment Station. Vicksberg, 1947), p. 8.
2. op. cit., p. 63.
3. op. cit., p. 65.
4. *The Thunderstorm,* pp. 50-1.

Maximum rates of precipitation occurred at the cell core from two to three minutes after the first rain reached the ground, and the rain remained very heavy for a period of from five to fifteen minutes. Then it decreased much more slowly than it increased. Lesser rainfall rates occurred around the edges of a cell.

The degree of instability associated with the summer storms investigated in these United States publications appears similar to that over Singapore[1,2], but it was not possible to confirm this by radiosonde data for 1953 for the present study. The upper-winds over the United States are normally much stronger than those over Singapore, so that the rate of travel of storms might not be similar in the two places. For that reason, the paths of storms, as well as their diameters and duration, are studied in the present work. In respect of rate of travel, Lutkin[3] states that individual cumuliform columns over Singapore follow the 10-30,000 ft. wind, though the general direction and rate of travel of the complete storm bear no relation to the wind at any level.

The representativeness of observations of rainfall depends on the size of individual storms as well as on their speed and path. Lutkin[4] discusses measurements of storms over Singapore made by the Royal Air Force with 3 c.m. and 10 c.m. radar during 1946 and 1947. From photographs of the plan position indicator at five-minute and half-minute intervals, it was decided that 90 per cent. of the storms consisted of numerous vertical columns each about one mile in diameter. This would mean that the daily rainfall should vary considerably over small horizontal distances. An investigation of this variation is, therefore, undertaken in the present study.

If the dimensions of individual storms are small, the frequency of rainfall recorded at different stations must vary as well as the actual amounts of rainfall. Stewart, Moorhead and Lea[5] show that a single gauge records about 15 rain-days per month at Singapore, which could signify that:

(a) showers are present daily and that half of a large number of gauges on the Island receive precipitation, or

(b) showers are present on half the month only, and one gauge records all falls. As neither of these propositions may apply alone, the present investigation includes a search for some optimum number of gauges which would more aptly describe rain-days over the Island.

Beebe has made an investigation of the number of stations necessary to define rain-days during showery conditions in areas within 50 miles radius of Birmingham and Atlanta Airports, U.S.A.[6]. He considered that, since convective showers moved with the prevailing winds during their life-cycle, fewer stations were required to determine the areal distribution of rain over a small area (disregarding the time of occurrence on a particular day) than to ascertain the maximum amount of rainfall near the thunderstorm centres.

1. Ibid, p. 20.
2. I.G. John, *The Properties of the Upper Air Over Singapore. Memoirs of the Malayan Met: Service*, No. 4 (Singapore, 1950), p. 13.
3. F.E. Lutkin, "The Use of Radar in the Location of Storms and Analysis of the Structure of Storm Systems," *Observations at Singapore. Reports by T.R.E. Division G (Asia), Malayan Meteorological Service Library* (Singapore, 1948), p. 23.
4. op. cit., pp. 1-26.
5. C.D. Stewart, H.B.F. Moorhead and C.A. Lea, *Annual Summary of Observations: Malayan Meteorological Service* (Singapore, 1925-41 and 1947-52).
6. R.G. Beebe, "The Distribution of Summer Storms over a Small Area," *Monthly Weather Review*, Vol. 80, No. 6 (Washington, D.C., 1952), pp. 95-8.

Taking a single station near Birmingham, rain occurred on 60 per cent of the summer days. By increasing the number of stations, there was a gradual increase in the number of days when rain occurred at any one of the selected number of gauges. However, there was no great increase in the number of rain-days when 30 or 40 gauges were employed. Therefore, it was assumed that 30 or 40 stations adequately described the areal rain-days in a circle of fifty miles radius in showery conditions.

Causie has made a similar investigation into the definition of rain-days per month[1]. Considering the daily rainfall from twenty stations in an area of 4,000 square miles in Nebraska, he decided that the scattering of summer showers there was similar to that over Atlanta described by Beebe. On plotting the "Number of stations used" against "Percentage of rain-days" and then joining the points, it was found that the resulting curve became nearly asymptotic to the 60 per cent. rain-days ordinate when 15-20 stations were employed.

(5) APPLICABILITY OF A TYPE OF SYNOPTIC WEATHER-ANALYSIS AT LOW LATITUDES

Opinions vary as to what form of synoptic weather-analysis should be used at low latitudes. Forsdyke[2] uses the 'frontal' methods of middle latitudes in analysing tropical charts, while Palmer[3] considers that any system resembling frontal analysis is inapplicable.

Watts[4] and Mather[5] demonstrate the application in Malaya of a method which recognizes semi-permanent discontinuities in the wind-field. They assume that equatorial rainfall over flat terrain is not wholly the result of scattered convective columns, and that wind-stream discontinuities are accompanied by general rain. Both of these assumptions require proof. Another aspect which is not fully explained is the form of the rain pattern at a discontinuity.

1. O.Y. Causie, "The Distribution of Summer Showers over Small Areas," *Monthly Weather Review*, Vol. 81, No. 4 (Washington, D.C., 1953), pp. 111-4.
2. A.G. Forsdyke, *Synoptic Analysis in the Western Indian Ocean*: (East African Met. Service, Nairobi, 1948), pp 1-11.
3. C.E. Palmer, "Tropical Meteorology", *Compendium of Meteorology, American Met. Society* (Boston, 1951), pp. 859-80.
4. I.E.M. Watts. *The Equatorial Convergence Lines of the Malayan-East Indies Area. Memoirs of the Malayan Met. Service*, No. 3 (Singapore, 1949), 1-30.
5. R. Mather, unpublished data showing the correlation of rainfall areas with the location of convergence in the 3,000-ft. wind-streams. *Malayan Met. Service Library*. (1951).

CHAPTER II

EXISTING DATA AND THE DISTRIBUTION OF INSTRUMENTS OVER SINGAPORE DURING 1953

The following Singapore daily or monthly rainfall observations are available in the records of the Malayan Meteorological Service (See Fig. 6):

Kandang Kerbau Hospital	54 years	1875-1928
Tan Tock Seng Hospital	47 „	1871-1919
General Hospital	46 „	1874-1919
Pierce Reservoir	44 „	1904-47 (and later)
Sĕletar Reservoir	44 „	1904-47 („ „)
Woodleigh Filters	36 „	1912-47 („ „)
Killiney Estate	32 „	1884-1915
MacRitchie Reservoir	14 „	1931-40, 1948-51
Kallang Airport	11 „	1935-40, 1948-51
Botanic Gardens	8 „	1937-40, 1948-51
Mount Faber	5 „	1929-33
Changi R.A.F. Station	4 „	1948-51
Sĕletar Naval Base	4 „	1948-51
Tĕngah R.A.F. Station	3 „	1949-51
Sĕletar R.A.F. Station	3 „	1947-48-51
Blakang Mati	3 „	1949-51

Manual rain-gauges have also been recently established at Pasir Panjang Power Station, No. 9 Gate of Singapore Harbour Board, the P.W.D. Office at Paya Lebar, St. Andrew's School, St. Margaret's School and Tampenis Road (See Fig. 9). Those stations which have been observed over a long period are well-distributed over the central and southern portions of the Island, but elsewhere observations are few and short-period. A 5-in. Casella recording syphoning gauge was maintained at Mount Faber from January, 1929 to May, 1934, and a 5-in. tilting-syphon type at Kallang from June 1934 to January 1942 and from January 1948 onwards. The analyses therefrom are available to describe the diurnal variation of precipitation in the south. Automatic gauges were also established at:

Tĕngah R.A.F. Station	in January 1949	—	5-in. tilting-syphon type
Changi „ „ „ „	„	—	„ „ „ „
Sĕletar „ „ „ „	1953	—	„ „ „ „
No. 9 Gate, Singapore Harbour Board	„ March 1948	—	5-in. Casella syphon „
Telecommunications Dept., Jurong	from March 1949 to November 1952	—	„ „ „ „
MacRitchie Reservoir	in March 1949	—	„ „ „ „
P.W.D. Office, Paya Lebar	„ June 1952	—	„ „ „ „

The records of these are not of long enough duration or sufficiently well-distributed to contribute much to the study of diurnal variation or maximum intensity. In order to study problems of diurnal variation, rain-days, and the structure and movement of storms it was considered desirable to increase the number of recording gauges for a period of at least one year. Twenty-five Casella

syphoning recording rain-gauges (tropical pattern) arrived in Singapore in November 1952 and were made available for the present study. Syphoning gauges were chosen in preference to the tilting-syphon type since the later require more maintenance and adjustment than the former. The gauges would necessarily be under the care of untrained observers and the simpler type of instrument was therefore preferable.

In choosing sites for the gauges the aims initially were:—

(i) that the exposures should be representative of the surrounding area and that the distance from any obstacle should be at least twice the height of the obstacle[1].

(ii) that the gauges should, together with existing automatic gauges, form an evenly spaced network over the whole Island.

Two restrictions on the choice of sites were apparent from the start:

(i) As the instruments were valuable, they would need to be placed in a compound or guarded area.

(ii) They had to be in the care of reliable observers prepared to change the charts daily (including Sundays) and to check and adjust the instruments.

The Commissioner of Police gave permission for the installation of the gauges at Police Stations throughout the Island (and on some smaller neighbouring islands), and directed Police staff to carry out the observing work. Without this assistance the project could not have been undertaken as neither of the restrictions mentioned above could have been overcome. The Commissioner of Prisons gave approval for the installation of a gauge at Changi Gaol, which was maintained by the prison staff, and the Master Attendant allowed the installation of a gauge at Horsburgh Light, in the care of the Lighthouse Staff. Another gauge was at the Meteorological Office, Fullerton Building. The Master Attendant later gave approval for gauges to be established at Sultan Shoal and Raffles Light, to the south-west and south of Singapore respectively.

Twenty-two automatic gauges were installed at police stations during December 1952, of which nineteen were on the Island of Singapore, two on Pulau Ubin, a mile to the north-east, and one on Pulau Seraya, which is two miles to the south-west of Singapore (See Fig. 9). At the same time gauges were installed at Changi Gaol and Fullerton Building, while one was placed at Horsburgh Light in May 1953. Except perhaps in the west, the distribution was good and fulfilled the second of the aims noted above. Eighteen of the sites were well clear of obstructions, ten of the sites were fair, while four of them were barely satisfactory owing to their altitude or the proximity of buildings and trees. However, the rule laid down in the *Observer's Handbook* as to the minimum distance of obstacles is designed to avoid decreased catch in the high winds of temperate latitudes, and it does not necessarily apply near the Equator. An analysis of surface winds at Kallang over a period of five years is shown below.

WIND-SPEED (M.P.H.)	CALM	1-3	4-7	8-12	13-18	OVER 18
PERCENTAGE OF TOTAL TIME	17.2	34.1	28.8	17.9	2.0	0

Lenard found that the diameters of rain-drops occurring most frequently in rain from shower or thunder-clouds were about 1-2 mm., and this value would probably apply to most tropical rains because they are convective[2]. The terminal

1. As recommended in the *Observer's Handbook* (M.O.4, Air Ministry, London; 1952), p. 149.
2. P. Lenard, "Uber Regen," *Meteorologische Zeitschrift*, vol. 21 (Braunschweig, 1904), pp. 249-62.

velocity of such drops is 4½-6 metres per second. As the wind near the surface at Singapore is rarely more than 12 m.p.h. (5·4 metres per second), it appears that obstacles could be about the same distance from the gauge as they are above ground-level without greatly affecting the catch. This was therefore taken as the limiting value in selecting sites, but it was approached in only a few cases.

Normal meteorological practice is to have a manual gauge beside an automatic gauge as a check. This was dispensed with since the extra observing work involved was too much to ask of the observers and because the automatic gauges were all to be checked daily with a measured amount of water. In further justification for using automatic gauges alone, the following shows that, at the stations where manual gauges were sited permanently, the errors in the daily totals of the automatic gauges were small.

STATION	No. OF DAYS (JUNE 1953)				
	NO RAIN	MANUAL EQUALS AUTOMATIC	MANUAL-AUTOMATIC EQUALS 0.02 IN.	MANUAL-AUTOMATIC EQUALS 0.01 IN.	AUTOMATIC-MANUAL EQUALS 0.01 IN.
MacRITCHIE RESERVOIR	15	12	1	—	2
KALLANG AIRPORT	16	6	2	6	—
No. 9 GATE, HARBOUR BOARD	16	12	—	1	1

An exception was made at Horsburgh Light where both automatic and manual gauges were used. There was a choice of two sites at Horsburgh, both of which were on the roof of the living quarters and about 15-ft. from a 60-ft. tower, but the spacing was such that both would probably never be in the rain-shadow of the tower at the same time. An automatic gauge was placed in one site and a manual gauge in the other. In the analysis of the daily observations the larger of two totals was always accepted as the true total.

It was difficult to select sites in some built-up areas without putting gauges on top of buildings, the highest being Fullerton Building. Kendrew[1] states that placing gauges at different heights can lead to great discrepancies and that at Oxford, a gauge on a tower 112 ft. high caught 30 per cent less rain than one on the ground near by. Because it is difficult to understand such large discrepancies occurring through differences in height (as distinct from orographic sheltering), a test was made at Singapore. A manual gauge was placed in the Marine Police Compound (Empress Place), 120 ft. lower and 150 yards distant from the Fullerton Building gauge, and daily measurements were made at both for 49 days in January and February 1954. On 22 of these days both gauges registered nil; on 22 other days the gauges differed by less than 0.05 in., while the falls on the remaining five days were:

FULLERTON BUILDING	2.04	0.60	1.33	0.10	0.80 IN.
MARINE POLICE	2.26	0.50	1.45	0.03	1.32 ,,

1. W. G. Kendrew, *Climatology* (Oxford, 1949), p. 175.

Fullerton Building's total rainfall for the period was 9 per cent less than that at the lower level. As the differences were so small and variable and occurred only on the wetter days, it was considered they were due to the local nature of the storms rather than the difference in height of the gauges. It was considered that no correction for height of station was necessary in determining isohyetal patterns, though a separate investigation was commenced in 1954 to compare rainfall at three adjacent stations—the Bank of China, 230 ft; Fullerton Building, 140 ft; and the Marine Police Station, 20 ft., M.S.I.

The distribution of automatic gauges detailed below was maintained from 1st January to 31st December 1953, except that the Serangoon gauge had to be withdrawn in June 1953 owing to the closing of the Station there, and the Horsburgh gauge was not installed until May 1953.

1. Pasir Laba Searchlight Station: installed 23/12/52. Fairly good open site on turf-covered, concrete building on side of hill.
2. Tuas Police Station: installed 29/12/52. Fair site, on top of a bank to right front of Station.
3. Lim Chu Kang Police Station: installed 18/12/52. Excellent open site in gravel yard to left rear of Station.
4. Tĕngah R.A.F. Station: permanent gauge in good site.
5. Jurong Police Station: installed 29/12/52. Fair site on grass just to left of path in front of building.
6. Tanjong Kling Police Station: installed 23/12/52. Fairly open site at edge of sea to left of Station.
7. Woodlands Police Station: installed 28/12/52. Rather poor site on lawn directly in front of building.
8. Nee Soon Police Station: installed 17/12/52. Very good open site on large lawn to left rear of Station.
9. Bukit Panjang Police Station: installed 1/12/52. Excellent open site on raised lawn to front left of Station, well back from road.
10. Bukit Timah Police Station: installed 21/12/52. Fair site on lawn to right front of building.
11. Holland Road Police Station: installed 21/12/52 Good open site on grass bank to left rear of building.
12. Pasir Panjang Police Station: installed 21/12/52. Poor site on sand close to left front of building.
13. Harbour Board, Gate No. 9: permanent gauge in good site.
14. Sĕmbawang Police Station: installed 28/12/52. Fair site on grass to right front of building.
15. Sĕletar R.A.F. Station: permanent gauge in good site.
16. Yio Chu Kang Police Station: installed 17/12/52. Fair site on enclosed grass area to left rear of Station.
17. Sĕrangoon Police Station: installed 16/12/52. Fair site in corner of Police compound near water's edge and near end of Serangoon Road. Withdrawn June 1953.
18. Paya Lebar Police Station: installed 16/12/52. Good open site on lawn in front of station near Paya Lebar Road.
19. Jalan Eunos Police Station: installed 22/12/52. Fair site near path between buildings.

20. Thomson Road Police Station: installed 28/12/52. Good open site on centre front of lawn before Station.
21. Kallang Airport: permanent gauge in good site.
22. Joo Chiat Police Station: installed 19/12/52. Fair open site outside Police Station compound on grass lawn, but near gate with permanent Police guard.
23. P.W.D. Office, Paya Lebar Aerodrome: permanent gauge on fair site.
24. Changi R.A.F. Station: permanent gauge on good site.
25. Changi Gaol: installed 22/12/52. Fairy open site in central courtyard between buildings.
26. Bedok Police Station: installed 19/12/52. Site only fair, in left front corner of compound.
27. Pulau Ubin (south) Police Station: installed 29/12/52. Site only fair, between two coconut trees.
28. Pulau Ubin (north), Kampong Bahru: installed 29/12/52. Good open site on turf-covered building.
29. Pulau Seraya Padang: installed 23/12/52. Very good site near padang, 100 yds. inland from constable's house.
30. Fullerton Building: installed 31/12/52. Well exposed position on roof above 5th floor of building.
31. MacRitchie Reservoir: permanent gauge on good site.
32. Horsburgh Lighthouse: installed 28/5/53. Automatic gauge and manual gauge on roof of concrete quarters 40 ft. above sea-level. Lighthouse tower 15 ft. away. Gauges well exposed to north; possibly some sheltering of one gauge from south.

Following the determination of an optimum distribution of gauges to record rain-days, a redistribution was made in the first three weeks of January 1954 to establish a permanent network. At the same time a very close network was set up using Police Stations in the urban area to study the isohyetal patterns of storms of small extent over a long period.

Normal practice in installing a permanent gauge is to have the base buried or placed in a hollow in the ground so that the top rim is one foot above the general ground-level, some provision being made for drainage from the base of the gauge. This was not carried out in the project because occasional redistribution of the gauges was envisaged, and care had to be taken to interfere as little as possible with the lawns on which most of the instruments were placed. Instead, wooden tripods were made with sharpened legs which could be driven into the turf, and the bottom rim of the gauge-base was screwed down to the top of the tripod. Thus the average height of the top rim of the gauge was 30 in. above ground-level, which is 18 in. in excess of that specified in the *Observer's Handbook*[1]. However, the resulting error in catch is small. Kendrew[2] states that from measurements made in North Germany during summer, it was found that a gauge with rim one metre above ground-level caught only about 3 per cent less than a gauge one foot high (difference in height is 27 in.).

1. *Observer's Handbook*, p. 149.
2. W. G. Kendrew, op. cit., p. 175.

Instructions, in English and Malay, issued to the observers included the following:

(1) Charts were to be changed daily between 08.30 and 09.30 hrs. (L.T.) and the exact time of the change was to be recorded on the charts.

(2) Pens were to be inked at least once per day.

(3) The accuracy of measurement of rainfall was to be checked daily by pouring in the equivalent of one inch of rain with a glass measure provided.

(4) The collecting funnel and the wire-gauze filter above the float container were to be cleaned daily.

(5) The glass disc above the syphon was to be cleaned monthly with carbon tetrachloride.

(6) Defects in the instruments were to be reported by telephone to the Malayan Meteorological Service.

After some difficulties in the first month of operation, all the gauges functioned well. Timing of change of charts was usually accurate to about five minutes, though in a few cases larger errors were detected. The gauges measured rainfall amounts as accurately as the coarse trace of the recording pen would permit. The records were collected each month, when new charts were issued and the gauges inspected.

In processing the records the basic method was a form of analysis in current use in the Malayan Meteorological Service. The quantities of rain for every hour and duration (in minutes up to one hour) were extracted from the charts and tabulated on one sheet for each month for each gauge. Analyses of these gave the mean hourly rainfall (24 hours) for each gauge for each month of 1953. From them could also be determined total monthly rainfall, rain-days and periods of general rain. It was soon realized that the short life of individual storms precluded the use of isohyets drawn from the hourly readings to study the behaviour of the storms. For this purpose it was necessary to analyse the charts according to half-hourly rainfall; an even shorter period was preferable but was impracticable owing to the errors made by the observers in timing the gauges.

CHAPTER III

MEAN RAINFALL OVER SINGAPORE.

(1) OFFICIAL RAINFALL RECORDS

The official records for Singapore usually quoted by the Malayan Meteorological Service date back to 1869 and refer to five different observing sites:

Convict Prison	1869-74
Kandang Kerbau	1875-1928
Mount Faber	1829-34
Kallang Airport	1934-41
Botanic Gardens	1942-47
Kallang Airport	1948-53

The official mean annual fall from this series is 95·48 inches, but annual totals fluctuate greatly (Fig. 3), the highest in eighty-five years being 135·92 inches and the lowest 63·21 inches.

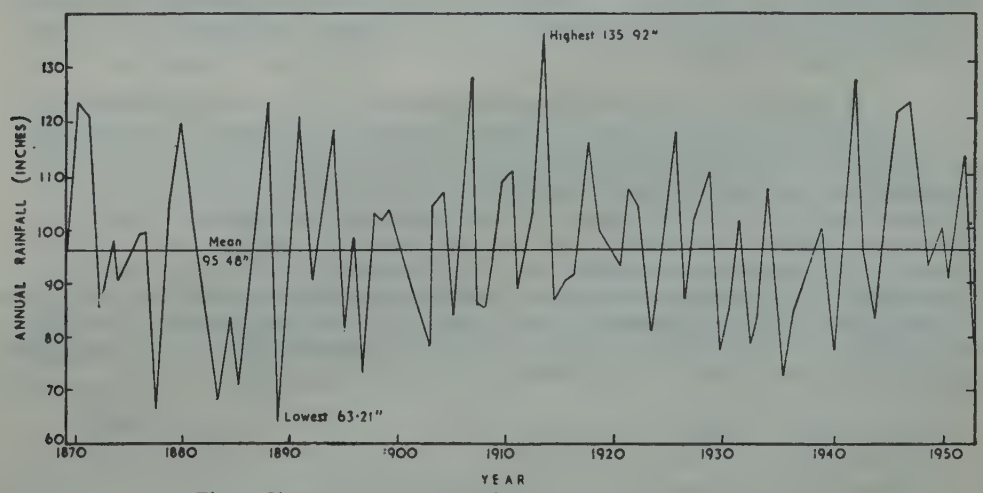

Fig. 3 Singapore: variation of annual rainfall, 1869-1953.

(2) PRECIPITATION AVERAGE AND RELATION OF SEASONAL VARIATION TO PREVAILING WINDS.

Daily rainfall has been recorded at each of six stations on Singapore Island for long periods of from thirty-two to forty-six years. These stations are Seletar Reservoir, Pierce Reservoir, Woodleigh Filters, Kandang Kerbau Hospital, Killiney Estate (Tanglin) and the General Hospital (Sepoy Lines)[1].

There is little difference between the mean monthly falls at the six stations during January, June and December (Table 2). In July and August the mean

1. Records for 47 years are also available for Tan Tock Seng Hospital, but at some time the site of this station was changed and the records are not necessarily representative.

TABLE 2: LONG-PERIOD MONTHLY AND ANNUAL RAINFALL

Station	Seletar	Pierce	Woodleigh	Kandang Kerbau	Killiney	General Hospital	Station	Seletar	Pierce	Woodleigh	Kandang Kerbau	Killiney	General Hospital
Period (years)	44	44	36	54	32	46	Period (years)	44	44	36	54	32	46
JAN							JUL						
Mean	10.42	10.50	10.43	10.61	10.52	9.86	Mean	5.91	5.35	5.06	6.61	7.48	7.01
Standard Deviation	5.78	5.96	6.13	6.64	6.80	6.47	Standard Deviation	3.06	3.07	2.74	3.39	3.86	3.14
Absolute Maximum	25.58	24.78	22.94	32.23	29.26	26.20	Absolute Maximum	14.54	11.21	10.76	20.76	21.14	17.68
Absolute Minimum	0.72	2.79	2.14	1.99	1.71	1.51	Absolute Minimum	0.47	0.83	0.84	1.03	1.43	0.62
FEB							AUG						
Mean	7.82	7.88	7.67	7.13	7.19	5.86	Mean	7.00	6.34	6.66	7.70	7.34	7.33
Standard Deviation	4.55	3.99	4.34	4.69	4.53	4.48	Standard Deviation	3.36	2.96	3.22	3.87	3.81	3.80
Absolute Maximum	17.35	20.75	16.88	22.31	20.88	23.22	Absolute Maximum	16.42	15.15	17.12	20.74	18.62	19.24
Absolute Minimum	0.51	0.90	0.32	0.88	0.84	0.86	Absolute Minimum	1.40	1.27	0.72	0.71	1.13	1.45
MAR							SEP						
Mean	9.87	9.73	9.06	7.71	7.76	6.05	Mean	7.35	6.96	7.24	6.74	6.62	6.99
Standard Deviation	4.43	4.56	4.61	4.57	4.99	3.79	Standard Deviation	3.07	2.87	2.67	2.50	2.34	3.05
Absolute Maximum	21.94	22.27	22.53	20.80	22.79	18.09	Absolute Maximum	15.57	13.59	13.19	12.13	11.96	16.71
Absolute Minimum	0.78	2.07	1.31	0.73	0.97	0.90	Absolute Minimum	1.86	1.66	2.48	2.42	2.84	2.12
APR							OCT						
Mean	8.99	8.55	8.06	7.55	7.61	6.59	Mean	9.49	8.93	7.87	8.29	8.07	8.49
Standard Deviation	2.75	3.23	2.56	3.07	2.80	3.05	Standard Deviation	3.90	3.39	2.93	3.21	2.97	3.36
Absolute Maximum	16.98	16.36	14.03	17.91	14.07	18.94	Absolute Maximum	16.49	17.21	14.23	15.86	13.94	18.59
Absolute Minimum	4.65	3.82	2.36	2.42	3.55	1.15	Absolute Minimum	4.68	3.09	3.01	1.25	2.72	2.21
MAY							NOV						
Mean	8.39	7.53	7.29	6.93	6.48	6.83	Mean	10.39	9.96	9.59	9.83	9.47	9.64
Standard Deviation	2.98	3.00	2.89	2.93	2.69	2.63	Standard Deviation	3.15	3.05	3.45	3.48	3.44	3.88
Absolute Maximum	15.20	16.09	15.91	15.22	15.50	16.52	Absolute Maximum	18.64	17.34	17.73	17.89	17.29	17.93
Absolute Minimum	2.41	1.96	2.54	2.57	3.31	2.68	Absolute Minimum	3.68	4.27	4.42	3.59	3.76	3.19
JUN							DEC						
Mean	6.93	6.14	6.04	6.82	6.87	7.54	Mean	10.80	10.42	10.20	10.23	11.75	10.51
Standard Deviation	2.98	2.72	2.11	2.70	2.16	3.45	Standard Deviation	4.70	4.72	4.82	3.68	4.30	4.03
Absolute Maximum	14.21	13.48	11.32	13.56	12.50	18.64	Absolute Maximum	22.45	24.17	26.15	19.48	22.67	19.67
Absolute Minimum	1.87	1.89	2.17	2.24	3.40	2.72	Absolute Minimum	4.32	4.09	3.17	3.73	6.04	4.49

Station		Seletar	Pierce	Woodleigh	Kandang Kerbau	Killiney	General Hospital
Period (years)		44	44	36	54	32	46
Annual	Mean	103.36	98.20	95.17	96.15	97.16	92.70
	Standard Deviation	14.51	13.63	15.10	16.35	17.48	14.87
	Absolute Maximum	127.42	125.73	136.65	135.92	138.64	131.84
	Absolute Minimum	55.89	70.81	66.99	63.21	65.46	55.93

falls are greater in the south than in the north; from February to May, from September to November and for a year mean falls are higher in the north than in the south. However, these six stations are all confined to the central and southern portions of the island and differences are very slight. There is little difference between the absolute maximum and between the absolute minimum monthly falls at each station, and the standard deviations in each month are similar.

The precipitation average as defined by Solot[1] (the average of the means of the six long-period stations) and the average of the standard deviations are shown in Table 3.

TABLE 3: CENTRAL AND SOUTHERN SINGAPORE PRECIPITATION AVERAGE

Month	J	F	M	A	M	J	J	A	S	O	N	D	YEAR
Preecipitation (in)	10.39	7.26	8.36	7.89	7.24	6.72	6.24	7.06	6.98	8.52	9.81	10.65	97.14
Average Standard Deviation	6.30	4.43	4.49	2.91	2.85	2.69	3.21	3.50	2.75	3.29	3.41	4.37	15.32
30-Day Equivalent	10.06	7.71	8.09	7.89	7.01	6.72	6.04	6.83	6.98	8.25	9.81	10.31	—

This shows maxima in December and March and minima in July and February, although the February minimum is less pronounced if the totals are corrected to a thirty-day month. December-January is the wettest period and May-September the driest. This seasonal variation is related to seasonal changes in upper winds. Monthly hodographs of vector mean winds[2] at various levels are shown in Fig. 4.

Strong north-easterlies prevail in December and January (Fig. 4) when the warm moist North-East Monsoon current covers the South China Sea and extends southwards to Java. Orographic ascent then causes heavy falls on the east coast of Malaya, where January means are mostly over twelve inches and even over sixteen inches in many places (Fig. 5). The December-January maximum at Singapore is also to a certain extent related to orography, since some of the low-level Monsoon air is deflected down the east coast of Malaya as far as Singapore. This is confirmed by the fact that the mean January 3000-ft. wind is 070°/13 knots at Kota Bharu but 020°/13 knots at Singapore. Convergence occurs over Singapore from the influx of this diverted air together with air arriving in the unobstructed north-easterly stream, and a high total rainfall results. Rainfall is less in February, since the orographic effect decreases with the decreasing winds (Fig. 4) and because the current becomes less moist[3].

The low rainfall from May to September is common to all Malaya (Fig. 5) and eastern Sumatra. At this period the area is covered at high level by moderate to strong south-westerlies (Fig. 4) which constitute the southernmost fringe of the Indian South-West Monsoon. Malaya is then in the rain-shadow caused by the 6000 to 8000-ft. ranges of Sumatra. As evidence of this sheltering effect it may be seen that, although there are south-westerlies from 6000 ft. upwards at Singapore (Fig. 4), the low-level winds are southerlies and presumably from a different source.

March-April and October-November are the inter-monsoon months when, upper winds being light and variable (Fig. 4), convection is at its greatest over the whole area. The rainfall from numerous convective storms then maintains high monthly totals.

1. B. Solot, "Possibility of Long Range Precipitation Forecasting for the Hawaiian Islands", *Research Paper No. 28: U.S. Dept. of Commerce, Weather Bureau (Washington,* D.C., 1949), p. 2.
2. Each observation at each level is resolved into a west-east component ($Vw \rightarrow e$) and a north-south component $Vn \rightarrow s$, and the vector mean wind is the resultant of $\frac{\Sigma Vw \rightarrow e}{n}$ and $\frac{\Sigma Vn \rightarrow s}{n}$ where n is the number of observations.
3. I.G. John, "The Properties of the Upper Air Over Singapore", *Memoirs of the Malayan Meteorological Service,* No. 4 (Singapore, 1950), plate. 2.

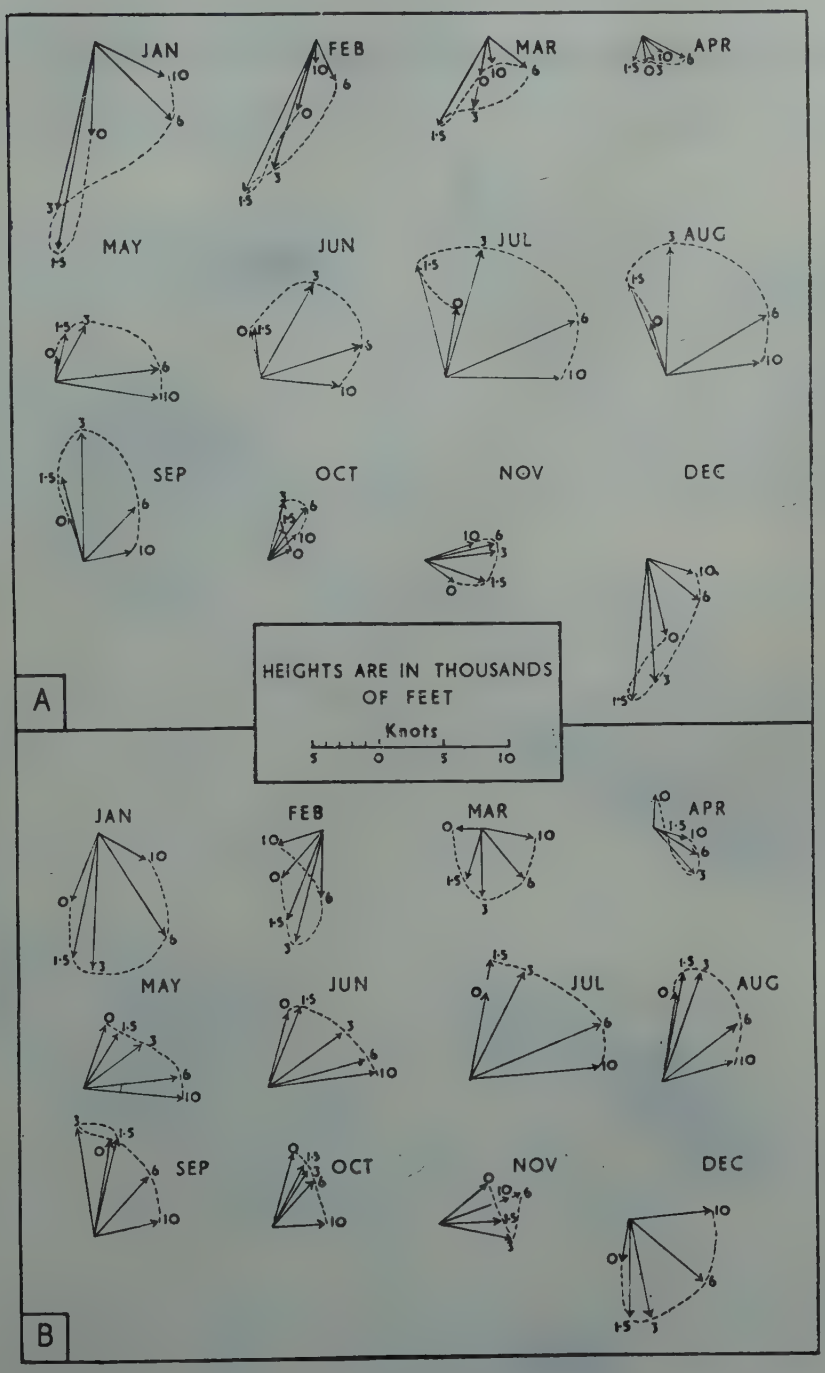

Fig. 4. Singapore: vector mean winds.
A. 06.20-08.20 hours, L.T.
B. 12.20-13.20 hours, L.T.
(Eight years, 1934-41).

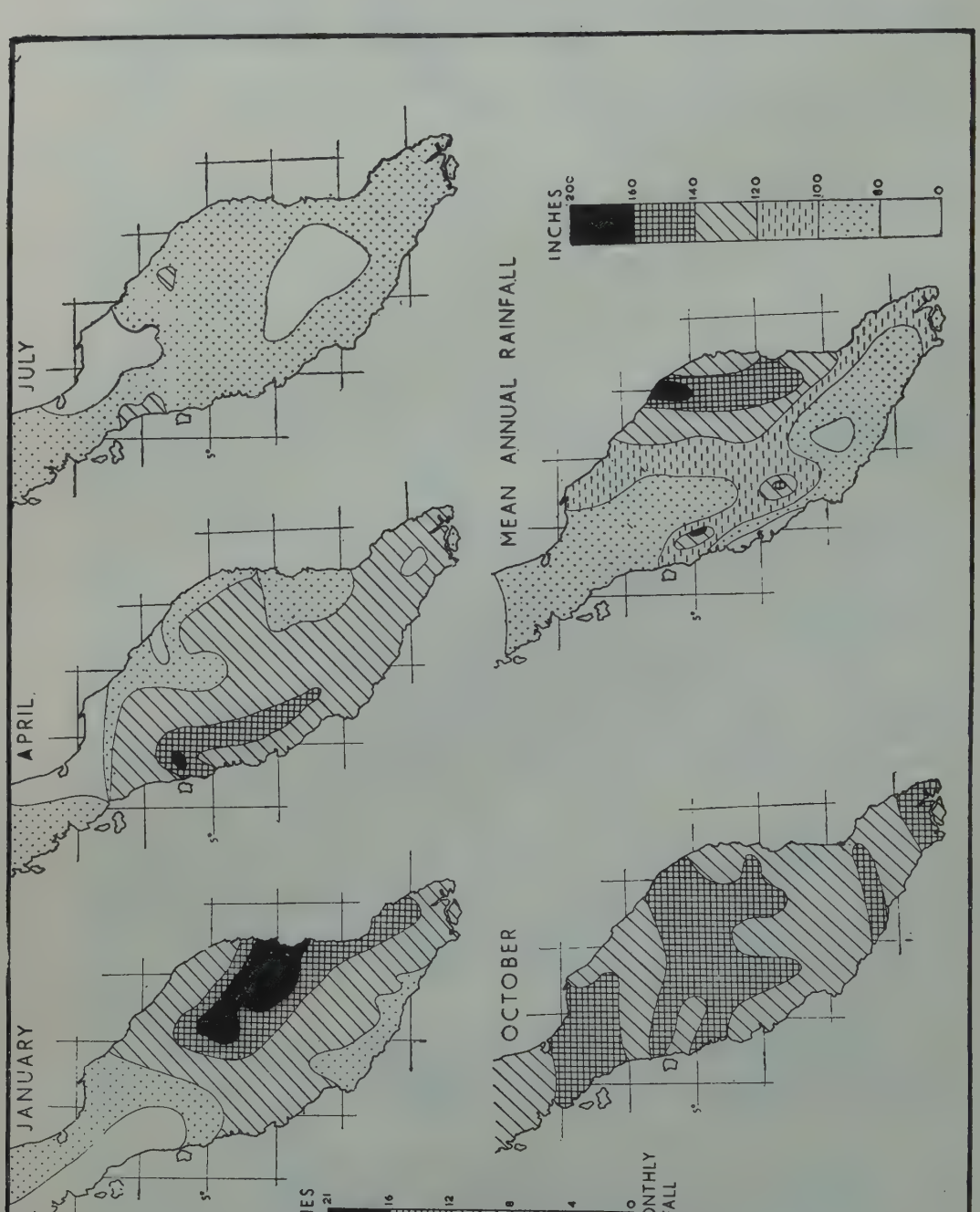

Fig. 5. Malaya: mean monthly and annual rainfall.

Holttum[1] uses monthly rainfall to show that the minimum in Singapore in February corresponds to the dry season at Batavia; but there is no evidence that the two are related. Reduction of each month to a standard length of thirty days would not only increase the Singapore February mean, but it would either erase all trace of a February minimum at Batavia or transfer that minimum to January.

(3) GEOGRAPHICAL DISTRIBUTION OF RAINFALL

Maps of mean annual and mean monthly rainfall over Singapore have been prepared from all available data (Figs. 7 & 8). Isohyets have been drawn at five-inch and one-inch intervals respectively, in order to show up any local effect. Where intrapolation was necessary the isohyets have been dotted.

Over the central and southern portions of the Island, records range from eight to forty-four years. Elsewhere they are mainly for the four-year period 1948-51 (p. 12). It is not possible to obtain means for each station for identical periods, but it is necessary at least to adjust the short-period means to compensate for any abnormal conditions occurring in those periods.

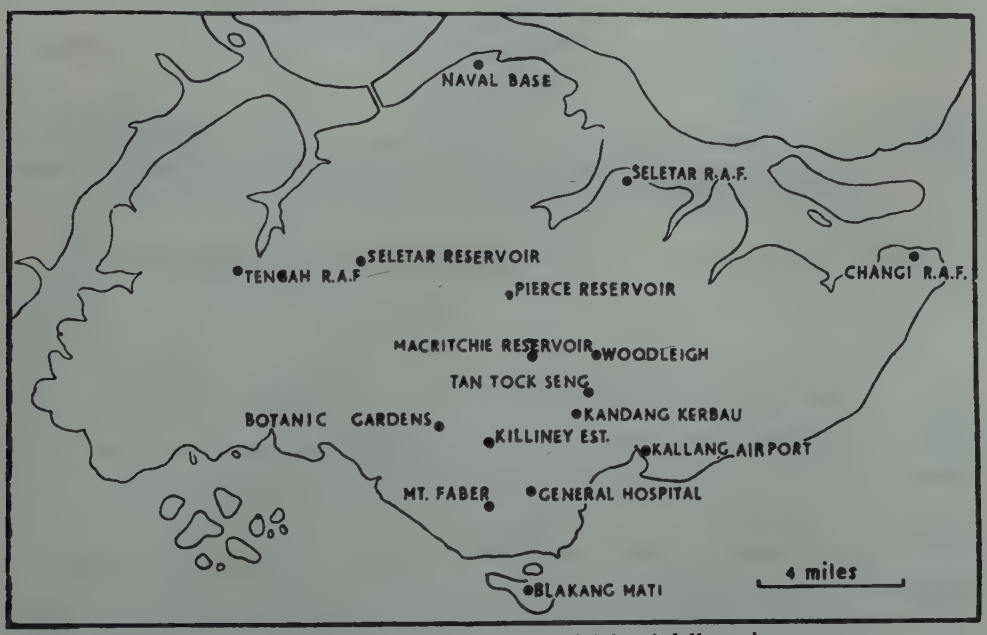

Fig. 6. Singapore: positions of official rainfall stations.

Table 4 shows that the differences between the 1948-51 means and the long-period means at Pierce, Woodleigh and Sĕletar exceed three inches in some months, and that in 1948-51 precipitation was generally greater than normal. Therefore, the mean monthly and annual values for Naval Base, Seletar, Changi, Tengah, Mt.

1. R.E. Holttum, "Evolutionary Trends in an Equatorial Climate", *Symposia of the Society of Experimental Biology*, No. 7 (Great Britain, 1953), p. 161.

Faber and Blakang Mati have been adjusted according to a method described by Leopold[1], and only the adjusted means are shown in Figs. 7 and 8. The adjustment was made thus: the mean rainfall for any month of 1948-51 at a short-period

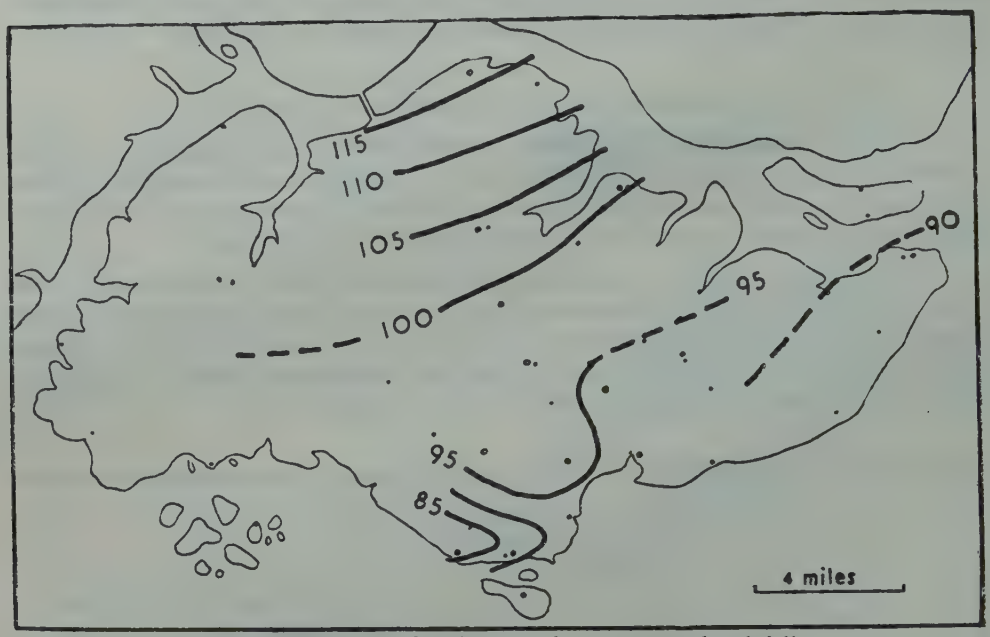

Fig. 7. Singapore: distribution of mean annual rainfall.

TABLE 4: COMPARISON OF LONG-PERIOD AVERAGES WITH THOSE FOR 1948-51.

	J	F	M	A	M	J	J	A	S	O	N	D	YEAR
PIERCE 44-YEAR MEAN.	10.50	7.88	9.73	8.55	7.53	6.14	5.35	6.34	6.96	8.93	9.96	10.42	98.20
1948-51 MEAN.	15.76	7.00	8.54	8.97	7.42	6.11	7.38	5.27	7.90	8.47	14.04	9.28	106.04
DIFFERENCE	-5.26	0.88	1.19	-0.42	0.11	0.03	-2.03	1.07	-0.94	0.46	-4.08	1.24	-7.84
WOODLEIGH 36-YEAR MEAN.	10.43	7.67	9.06	8.06	7.29	6.04	5.06	6.66	7.24	7.87	9.59	10.20	95.17
1948-51 MEAN.	14.04	6.42	8.41	8.31	6.61	5.79	7.88	3.91	6.99	7.52	10.91	11.85	98.64
DIFFERENCE	-3.61	1.25	0.65	-0.25	0.68	0.25	-2.82	2.75	0.25	0.35	-1.32	-1.65	-1.47
SELETAR 44-YEAR MEAN.	10.42	7.82	9.87	8.99	8.39	6.93	5.91	7.00	7.35	9.49	10.39	10.80	103.36
1948-51 MEAN.	16.36	8.83	10.30	10.22	8.72	6.50	6.98	5.76	8.69	9.05	11.92	9.74	113.07
DIFFERENCE	-5.94	-1.01	-0.43	-1.23	-0.33	-0.43	-1.07	1.24	-1.34	0.44	-1.53	1.06	-9.71

1. L.B. Leopold, "The Annual Rainfall of East Maui," *Hawaiian Planters' Record*, second issue (Honolulu, 1949), p. 50.

station was multiplied by the long-period mean for that month for Pierce, Woodleigh and Sĕletar divided by the 1948-51 mean for those stations.

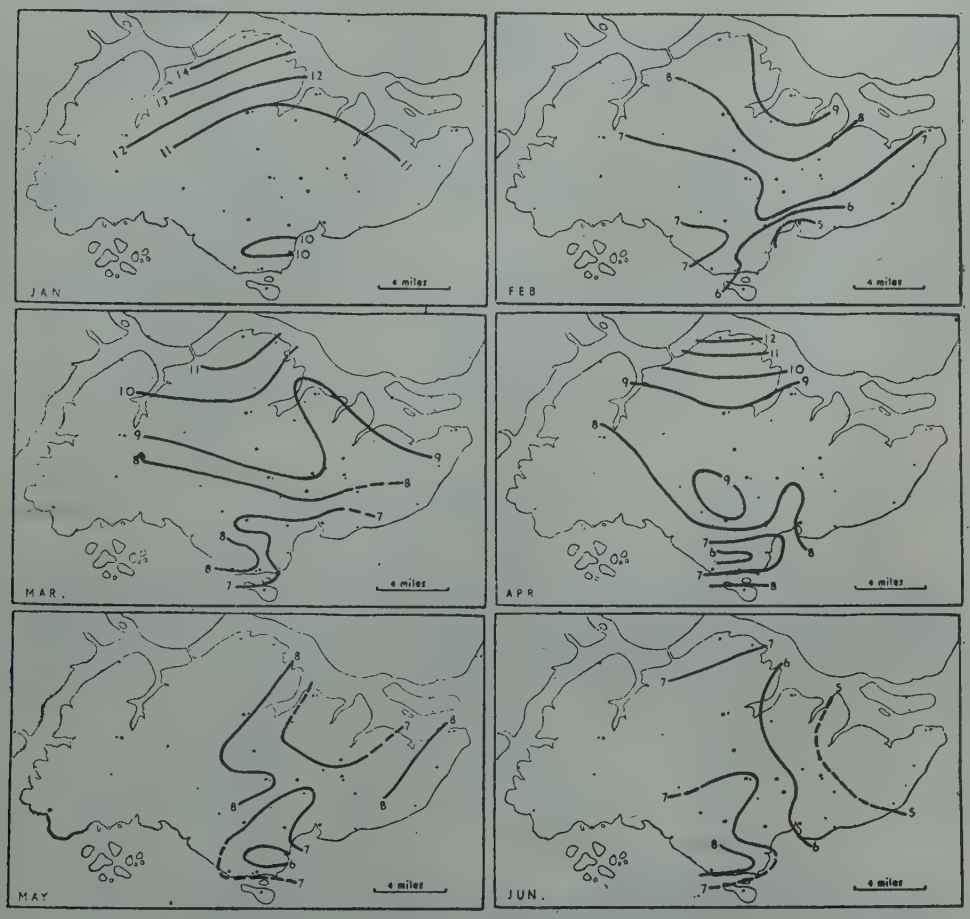

Fig. 8. Singapore: distribution of mean monthly rainfall, January-June.

From the isohyetal maps of Figs. 7 and 8 the following deductions may be made:

(1) In January there is a dry area of less than 10 in. per month about Mt. Faber[1]; mean monthly rainfall is elsewhere generally 10-11 in. except in the far north where it increases to at least 14 in.

(2) In February, mean monthly rainfall is 5-7 in. in the extreme south, 8-9 in. in the extreme north and elsewhere 6-8 in.

(3) In March, mean monthly rainfall varies from 6-8 in. in the south to nearly 12 in. in the north.

1. Although the peculiarity in Mt. Faber rainfall at this and other times might seen to be due to local screening, the gauge was in an exposed position near the top of the hill.

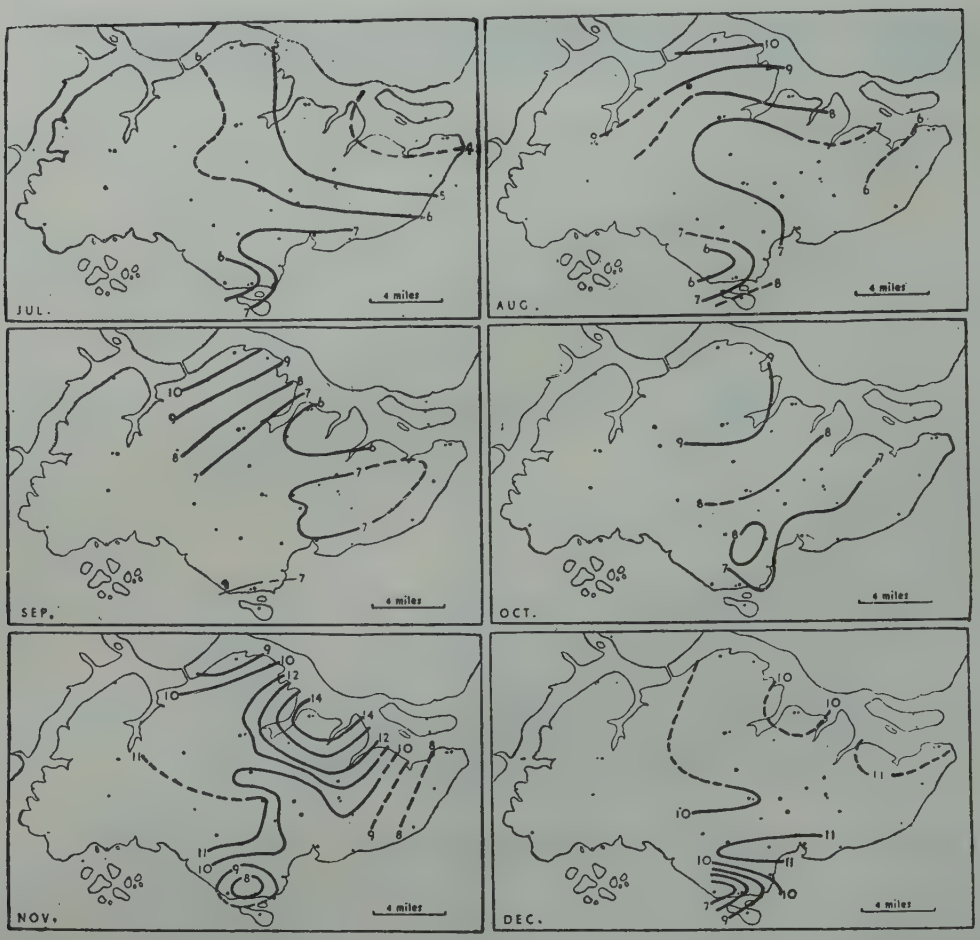

Fig. 8 (cont.). Singapore: distribution of mean monthly rainfall, July-December.

(4) In April, rainfall is between 5-8 in. in the south and totals 12 in. in the north.

(5) In May there is little variation from place to place, the monthly mean being everywhere between 6 and 9 in.

(6) In June mean rainfall varies from 4½ in. in the east to 6-7 in., except in the Mt. Faber area where it exceeds 8 in.

(7) In July the mean rainfall is 5-7 in., except in the north-east where it is below 4 in.

(8) In August rainfall is 6-8 in., except in the north where it exceeds 10 in.

(9) In September rainfall is generally 6-7 in., except in the north where it exceeds 10 in.

(10) In October the mean is about 9 in. in the north but 6-8 in. elsewhere.

(11) In November there are dry areas of less than 8 in. in the east and about Mt. Faber. Elsewhere the mean is mainly 9-11 in., increasing to over 14 in. near Sĕletar R.A.F. Station.

(12) In December rainfall is under 7 in. about Mt. Faber, elsewhere 9-11 in.

(13) Mean annual rainfall (Fig. 7) varies from 83-96 in. in the south (with a relatively dry area around Mt. Faber) to at least 115 in. in the north.

The outstanding facts invalidating the unqualified acceptance of the unadjusted short-period monthly rainfall means for the drawing of isohyets were the high January, July and November means and the low August means for 1948-51. The meteorological factors causing very low monthly rainfall totals must be large-scale features, because the absolute minimum total at any one station is associated with small totals at the others. For instance the lowest recorded August total at Woodleigh Filter was 0·72 in. in 1930. The totals at other stations for August 1930 were Kandang Kerbau 1·80 in. (mean 7·70), Seletar Reservoir 4·05 in. (mean 7·00) and Pierce Reservoir 1·69 in. (mean 6·34). Similarly it may be shown that the absolute maximum monthly total at any one station is associated with high totals at the others.

(4) MONTHLY AND ANNUAL ISOHYETAL PATTERNS OVER SINGAPORE FOR 1953

The means and corrected means used in constructing the normal rainfall maps of Figs. 7 and 8 inadequately covered the Island and isohyets to the east and west were drawn largely by extrapolation. How far this was justified may be seen by comparing the normal maps (Figs. 7 and 8) with maps of actual monthly and annual rainfall for 1953 (Figs. 10 and 11).

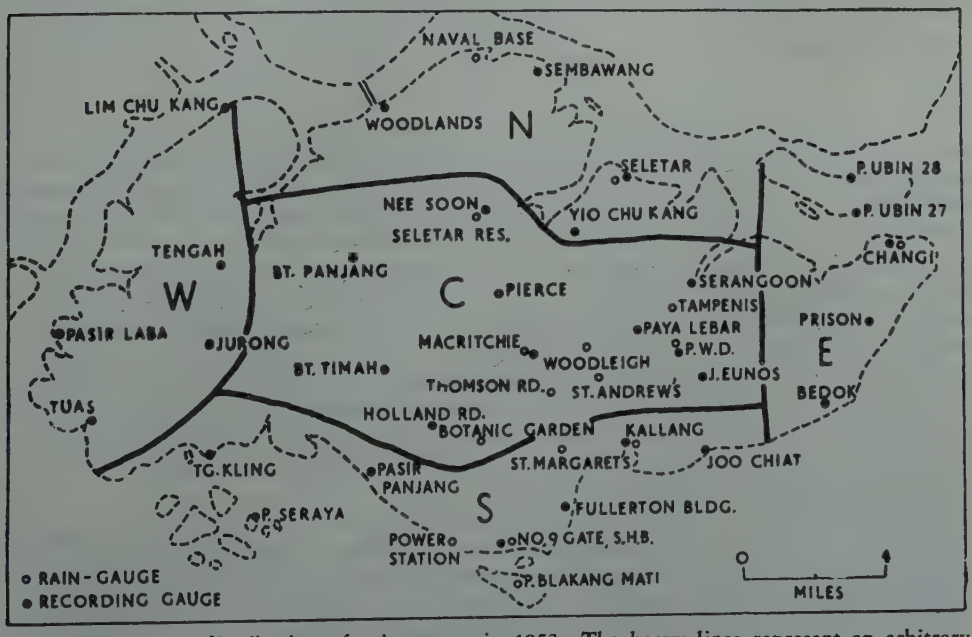

Fig. 9. Singapore: distribution of rain-gauges in 1953. The heavy lines represent an arbitrary division into rainfall provinces (See p. 35).

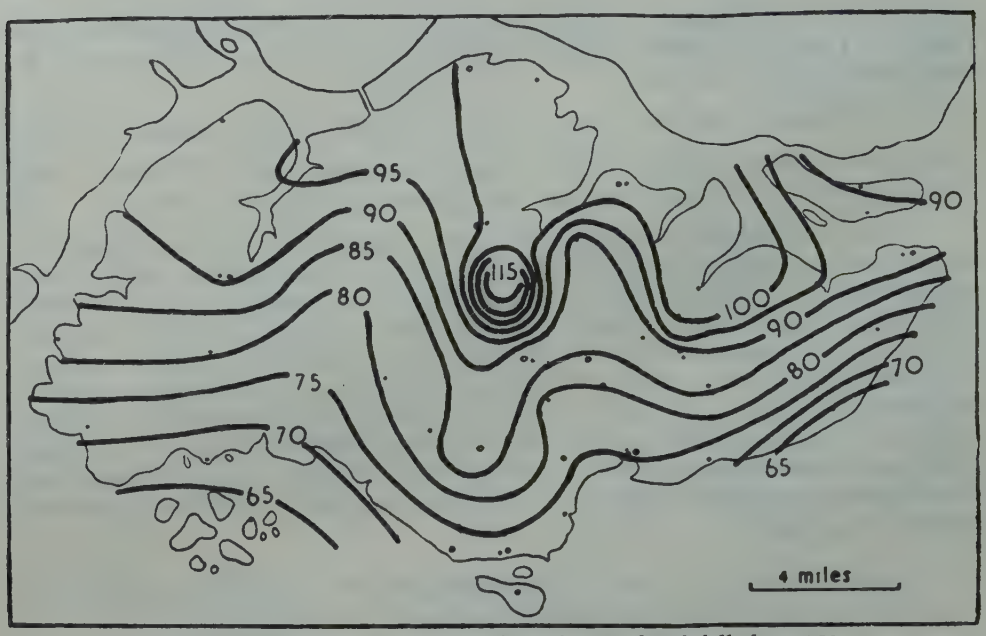

Fig. 10. Singapore: pattern of total annual rainfall for 1953.

The average annual rainfall during 1953 for the six stations selected earlier in this chapter for the determination of precipitation average was less than the

TABLE 5: SINGAPORE PRECIPITATION AVERAGE AND MONTHLY FALLS IN 1953

	J	F	M	A	M	J	J	A	S	O	N	D	YEAR
Precipitation Average	10.39	7.26	8.36	7.89	7.24	6.72	6.24	7.06	6.98	8.52	9.81	10.65	97.12
1953 Average	6.86	11.82	9.85	12.57	5.36	4.43	7.41	6.82	6.60	4.21	7.01	7.43	90.37

long term precipitation average (Table 5). Nevertheless, the 1953 annual rainfall pattern bears a general resemblance to the long-period mean annual rainfall pattern (of Figs. 7 and 10). That is, annual rainfall in 1953 was heavier in the north than in the south and the isohyets were concave northwards.

In 1953 the dry southern area of the normal maps did not appear and the area of greatest annual rainfall was near the centre of the Island. The 1953 monthly maps show that these high totals were brought about mainly by the heavy rain in the neighbourhood of Pierce Reservoir in February, April, July, September and November, which on more detailed analysis was largely the effect of a few very heavy falls of short duration. Thus during February 1953, 63 per cent of the month's rainfall came in three days and 33 per cent on a single day. Later investigation, using half-hourly isohyetal maps, has confirmed that most of the rain on these days occurred in brief storms.

January 1953 was drier than normal (Table 5), and although the usual north-south gradient of rainfall (Fig. 8) was maintained, the heavier falls were on the north-east coast rather than on the north-west coast. Since the average upper winds in January 1953 varied little from the long-period averages for January (Fig. 12), it is unlikely that the location of the heaviest falls on one part or another of the north coast is dependent on wind direction. It appears that the

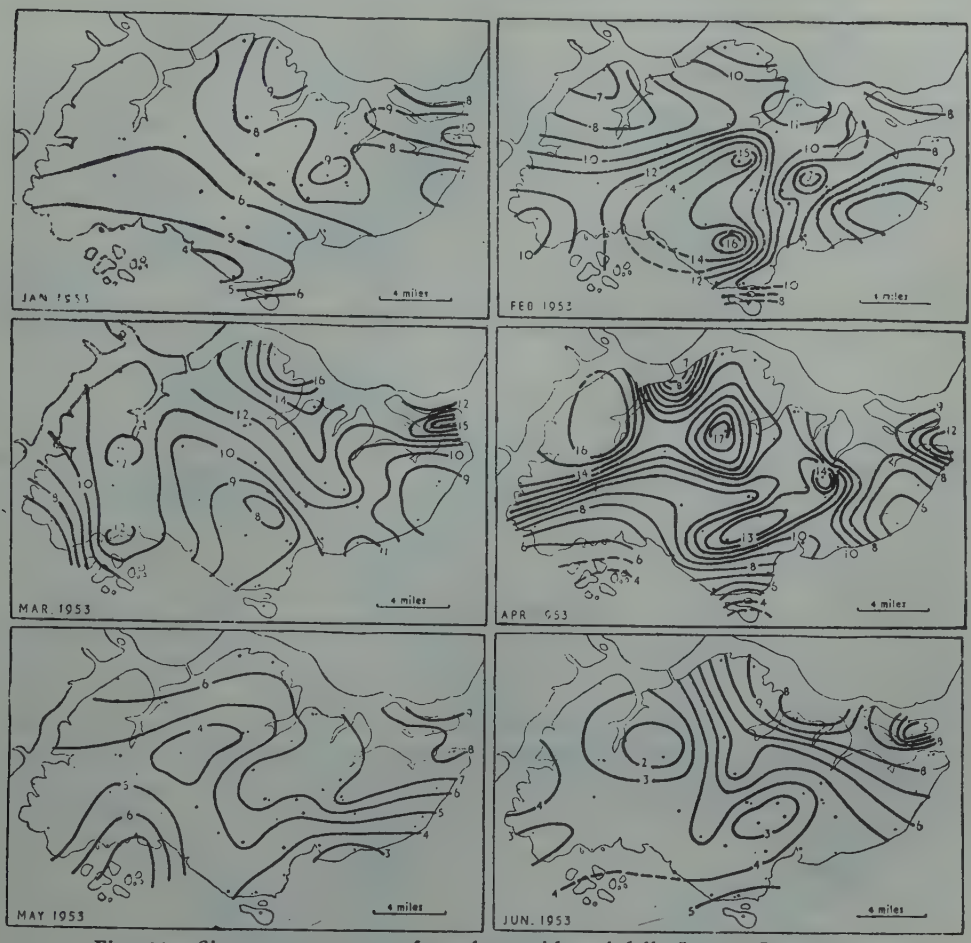

Fig. 11. Singapore: pattern of total monthly rainfall, January-June, 1953.

exact location of the heaviest falls on the north coast in a particular month is fortuitous. In February 1953 (Fig. 11), when there was much more rain than normal (Table 5), the highest totals were in the central area. Yet, it is unlikely that the normals (Fig. 8) were misleading here, where the records on which they were based covered the longest priods.

March 1953 (Fig. 11) was a little wetter than normal (Fig. 8), but the pattern was a reasonable confirmation of the normal pattern. Two new facts showed here: (i) in 1953 there was a north-south belt of heavy rainfall through Lim Chu Kang and Tanjong Kling, with a drier area in the south-west, and (ii) the 'normally' dry area over the city was in a different position.

It is not easy to reconcile the April 1953 pattern with the normal (Figs. 11 and 8). Because this is the inter-monsoon period when the general flow of wind is light (Fig. 4), convectional precipitation is usually prominent and an irregular pattern is to be expected. May-August and November-December isohyets in 1953 likewise bear little resemblance to the normal patterns (Figs. 8 and 11). The wetter areas of the long-period maps sometimes coincide with the drier areas of the 1953 maps. As the long-period maps for these months show little gradient of precipitation, it is probable that their isohyets are not significant.

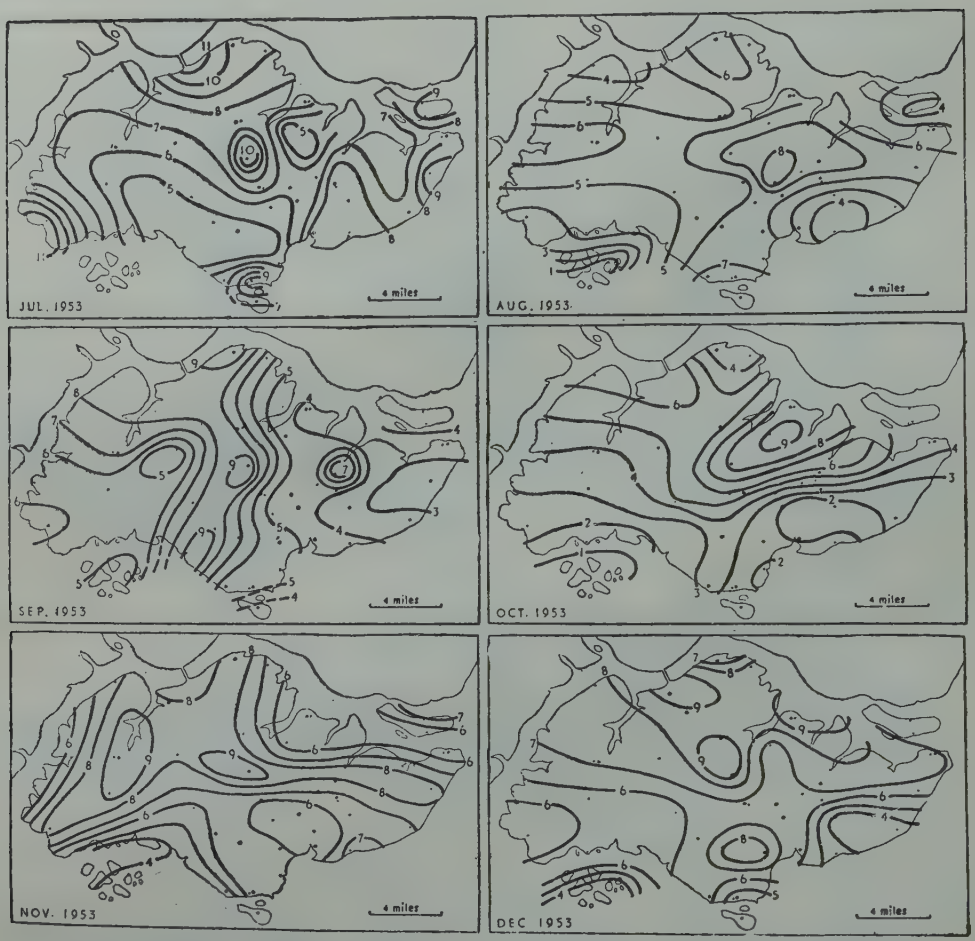

Fig. 11 (cont.). Singapore: pattern of total monthly rainfall, July-December, 1953.

The isohyets for September 1953 resemble the normal pattern in having most rainfall on the north to north-west coast with the eastern part of the island comparatively dry. Those for October 1953 are very different from the mean maps in the far north.

In general, therefore, it appears that the annual and monthly isohyetal patterns for the particular year 1953 bear only broad resemblances to the long-period mean patterns.

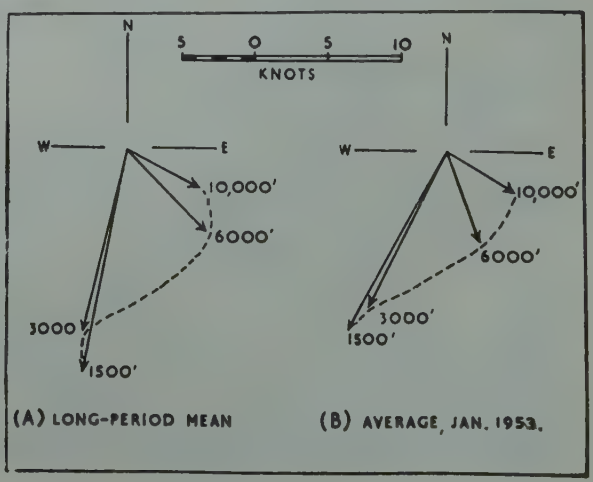

Fig. 12. Singapore: vector mean winds in January.
A. Long-period mean.
B. Average for January, 1953.

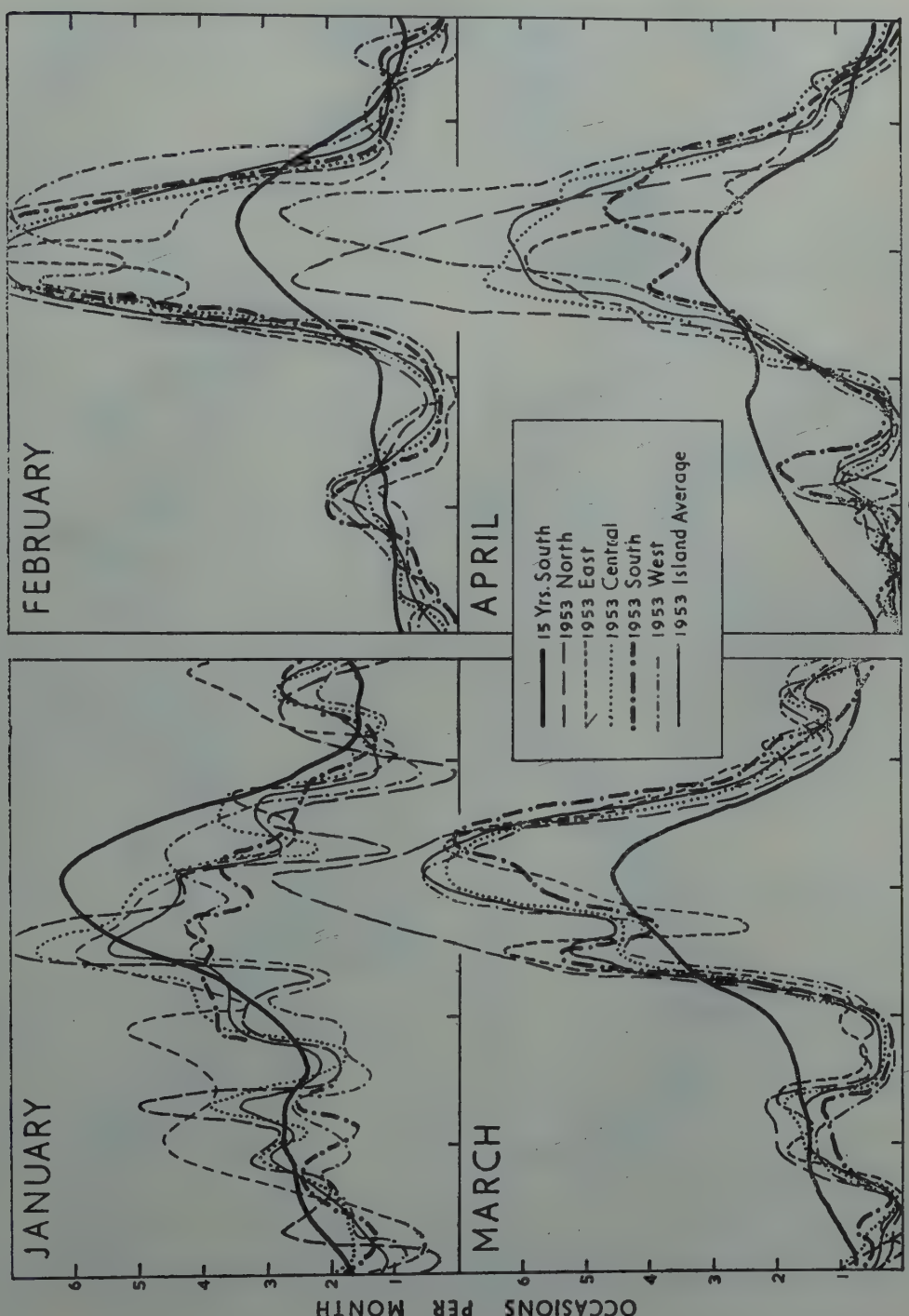

Fig. 13. Singapore: diurnal variation of precipitation, January-April.

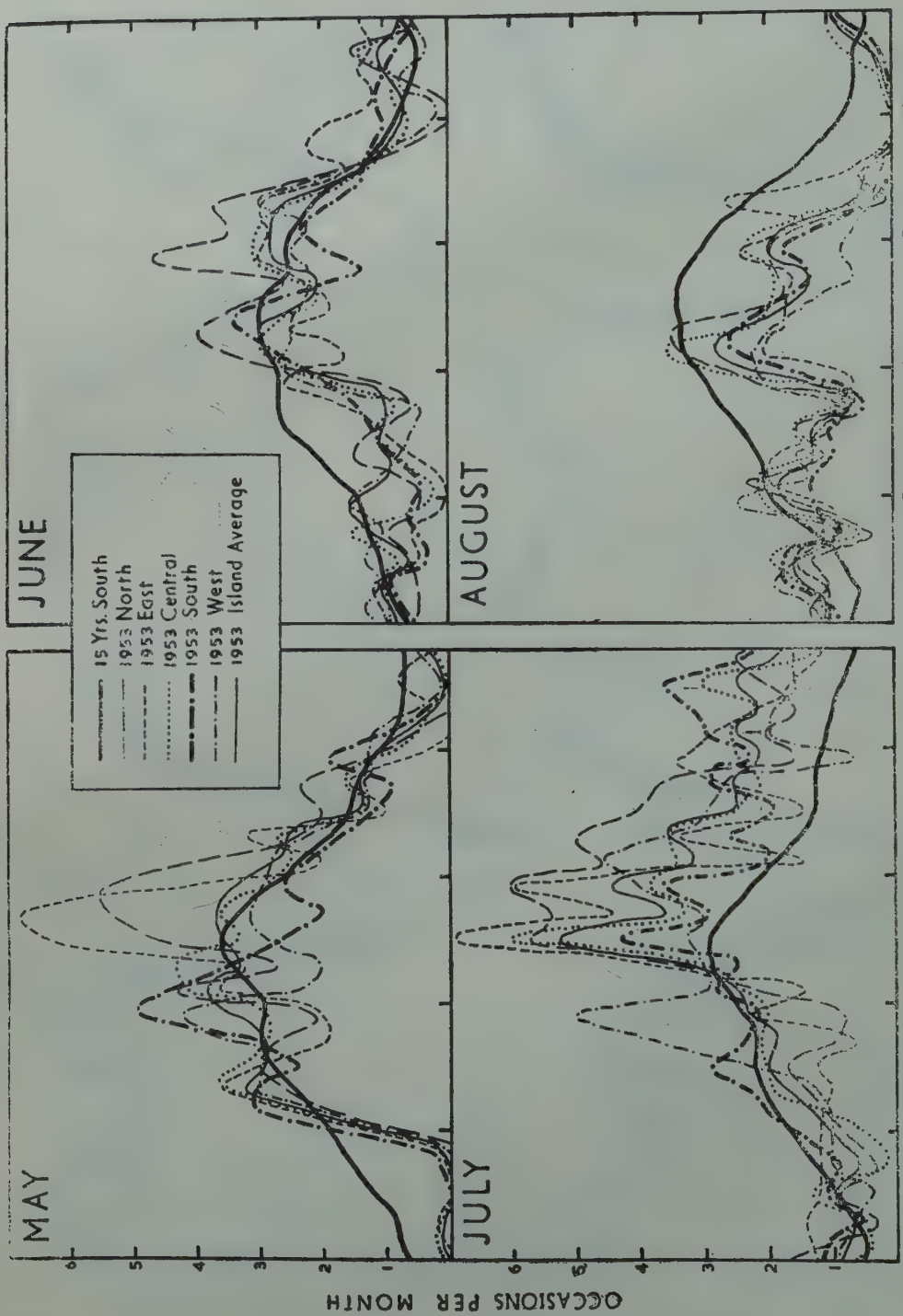

Fig. 13 (cont.) Singapore: diurnal variation of precipitation, May-August.

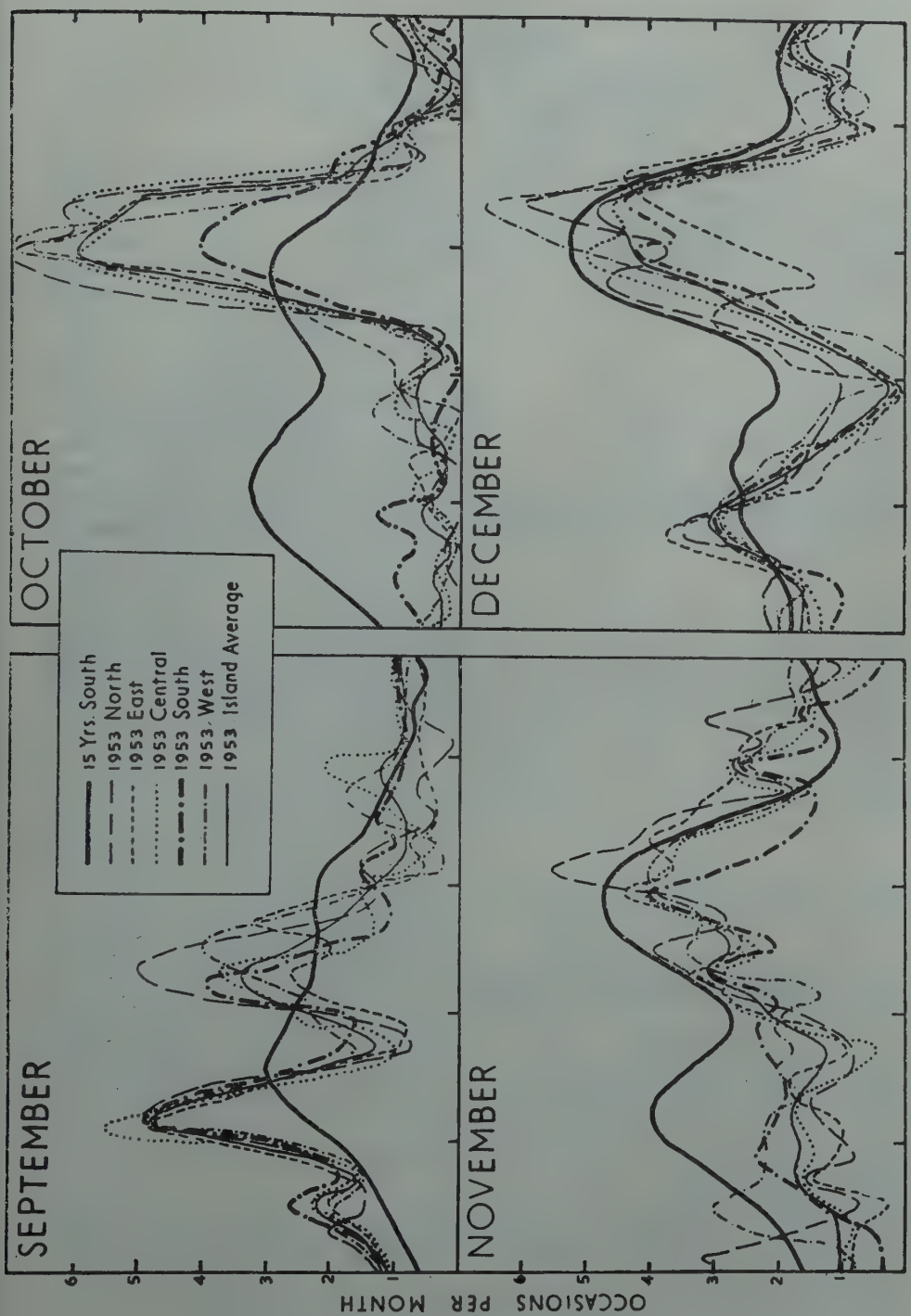

Fig. 13 (cont.). Singapore: diurnal variation of precipitation, September-December.

CHAPTER IV

DIURNAL VARIATION OF PRECIPITATION IN THE MEAN AND DURING 1953-4.

(1) VARIATION OVER LAND

The diurnal variation of frequency of precipitation at Singapore varies considerably throughout the year. This is illustrated in Fig. 13 (after Lea[1]), where the heavily drawn curves show the average number of occasions of precipitation at each hour of the day for each month. These curves are plotted from fifteen years' records of an autographic gauge at Mount Faber and later at Kallang Airport, and have been smoothed by plotting the average of each three consecutive hourly means. In recording an occasion of precipitation, a minimum fall of 0·01 in. per hour was taken in accordance with standard meteorological practice, but it may be seen from Fig. 14 that the peak of highest frequency would occur at the same time regardless of the minimum of precipitation adopted[2]. Similar curves could also be constructed by plotting the average hourly rainfall amounts instead of frequency of occurrence (see Fig. 15), as was found by Doraisamy in an investigation of rainfall at Colaba (Bombay)[3].

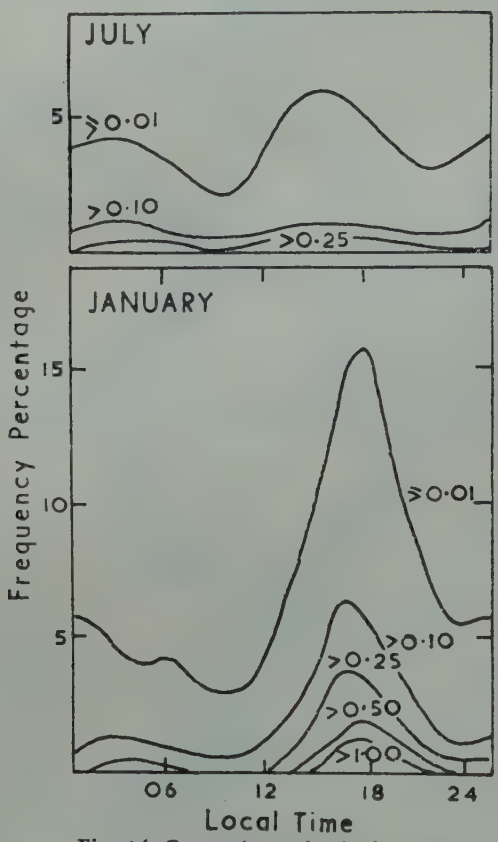

Fig. 14. Comparison of rain frequencies using different minima (Kuala Lumpur data, seventeen years).

The mean curves (the heavy unbroken lines of Fig. 13) show that from December to March rain is usually most frequent from 15.00 to 16.00 hours L.T., with a secondary maximum at about 06.00 hours in December and January. The afternoon maximum is probably due to local heating and the small morning maximum is part of an effect experienced over all the east coast of Malaya where precipitation develops in early-morning cumuliform build-up and moves landwards under the influence of the prevailing wind (see Fig. 4).

1. C.A. Lea, unpublished data on the diurnal variation of rainfall at Singapore, *Malayan Met. Service Library* (Singapore, 1950).
2. Kuala Lumpur data are used in this demonstration in order to show that the effect is independent of the nature of the precipitation. At Kuala Lumpur there is a greater seasonal effect and the annual range of monthly rainfall is greater than at Singapore. The data covered the seventeen years 1927-41 and 1948-9.
3. V. Doraisamy, "Diurnal variation at Colaba (Bombay) from an Analysis of Hourly Rainfall Records," *India Meteorological Department Scientific Notes*, vol 8, no. 99 (Delhi, 1941), pp. 159-60.

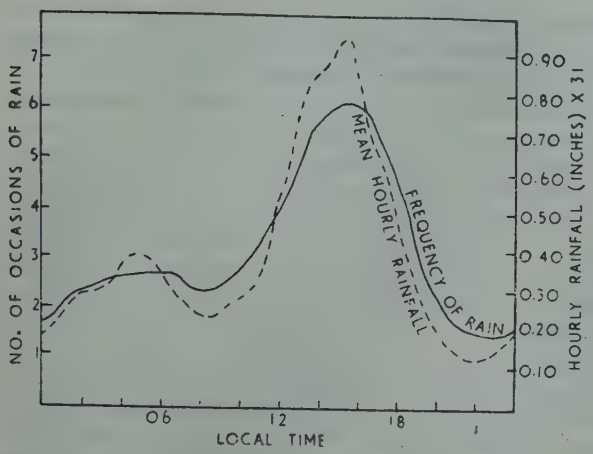

Fig. 15. Singapore: mean hourly frequency and amount of rainfall in January (Fifteen years: 1929-34, 1936-42, 1948-9).

After April the afternoon maximum decreases in prominence and early morning precipitation becomes more frequent, until in September and October most precipitation occurs at 06.00-08.00 hours L.T. Watts has shown that this condition is common to the west coast of Malaya south of Sitiawan, and that the high frequency of precipitation is caused by cumulonimbus developing in the Straits of Malacca and moving on to the land with the prevailing winds (south-westerly from May to October). Much of the early morning rain occurs in Sumatras, which are intense thunderstorms accompanied by strong squalls. It has been shown that the formation of Sumatras depends on the curvature of the Malayan and Sumatran coasts and on the Malayan land-breeze[2], while Sawyer[3] has suggested that the land-breeze from Sumatra may also contribute.

The frequency of occurrence of precipitation at each hour of each month in 1953 has been plotted in Fig. 13 to determine whether the diurnal variation differs with location across the island. For this purpose the Island has been arbitrarily divided into Northern, Eastern, Central, Southern and Western Sections (Fig. 9); the fifteen-year average for Kallang and Mount Faber corresponds with the Southern Section. The curves for each month of 1953 have been obtained by computing for each hour the average frequency of rain for all stations in a region. These regional hourly frequencies have then been plotted without smoothing. The curves showing diurnal variation over the whole island for each month in 1953 have been formed by plotting, at each hour, the average of frequencies of rainfall at every station on the Island.

The 1953 regional curves show differences from the fifteen-year mean curves, but there is a remarkable correspondence in the times of maximum frequency on all curves in any one month.

There are two notable features about the January curves. The highest frequency of precipitation over the whole Island was at 13.00 hours L.T. in 1953, compared with 15.00 hours in the long-period mean. This may possibly have been due to excessive instability accelerating the daily cumuliform development, but not apparently to any peculiarity in the upper-wind flow, which in January 1953 was practically identical with the normal for January (Fig. 12). Second, there was a high frequency of early morning precipitation over the Eastern and Northern Sections during January 1953, which is not evident in the other sections or in the

1. I.E.M. Watts, *Equatorial Weather* (London, 1955).
2. I.E.M. Watts, "The Line-squalls of Malaya". *Malayan Journal of Tropical Geography*, vol. 3 (Singapore, 1954), pp. 1-14.
3. J.S. Sawyer, *Cooling of Air By Rain as a Factor in Convection, Met. Office Prof. Note No. 96* (London, 1949), pp 1-11.

long-period curve. An examination of individual storms later indicated that this was mainly due to early morning precipitation moving from the sea to the exposed coast of the Island but dissipating before reaching the other coast.

In February 1953 the curves for various sections of the Island were similar, though frequencies were higher than normal. The timing of maximum frequency in 1953 was similar to the long-period curve but February 1953 had a secondary maximum at 05.00 hours L.T. Similar conditions were found in the March comparisons when storms formed haphazardly over the Island, except that afternoon precipitation was more frequent in the northern section than elsewhere (see the half-hourly isohyets of 4/3/53 and 21/3/53 in Figs. 23 and 24). The early morning falls of February and March 1953 were without parallel in the long-period curves.

In April, 1953 afternoon rain was much more frequent in the north and west than elsewhere, and there was a general morning peak, two to three hours earlier than that indicated by the long-period curve. In May 1953 the mid-day and early afternoon rain was most frequent in the north and east (see half-hourly isohyetal maps for 20/5/53 in Fig. 25); otherwise the curves were close to the long-period curves except that there was very little early morning rain in May 1953.

The June curves were all very close to one another and to the long-period curve, though afternoon rain was still a little more frequent in the north than elsewhere. In July, 1953 the time of peak frequency was the same as in the long-period mean, but afternoon showers were much more frequent. The early morning peak in July, 1953 was pronounced only in the south and west which indicated that the main effect of sumatras did not extend across the Island (see half-hourly isohyetal maps of 14/7/53 in Fig. 26). Afternoon rains in July, on the other hand, were more common in the north and east.

August, 1953 had a more clearly defined early morning secondary peak by comparison with the long-period curves.

September, 1953 was remarkable in that the very frequent occurrence of early morning rain showed no variation across the Island. Both peaks of maximum frequency in 1953 were from two to three hours earlier than normal, and the mid-day rains were a little more common in the north than elsewhere.

In October 1953 early morning rains were rare while afternoon occurrences were more pronounced than normal. There was little variation of frequency over the Island, but afternoon rains were least in the south.

The peaks of highest frequency for the whole Island in November, 1953 occurred at about the same time as those of the long-period curves, except that early morning rain was a little earlier in the north and west than elsewhere, while afternoon showers were most common in the north.

Curves for December, 1953 are like the normal, though early morning falls were most common in the north and east, which could be accounted for by the North-East Monsoon winds (see Fig. 4). Afternoon falls in December, 1953 were most prominent in the west.

It appears, therefore, that the long-period average curves are fairly representative of actual conditions in any particular month. The diurnal variation is much the same in different parts of the Island during a particular month. There is an indication that in the middle of the monsoons (December-January and in July) when the winds are strongest, morning rain may be mostly on the exposed coast and afternoon rain mostly toward the sheltered side of the island, but this could not be determined without autographic records from several gauges over a long period.

(2) VARIATION OVER SEA

As the early morning peak of rainfall on Singapore Island appears to be due to showers drifting in from the sea, an examination has been made of the diurnal variation offshore. Fig. 16 compares the diurnal variation of precipitation at

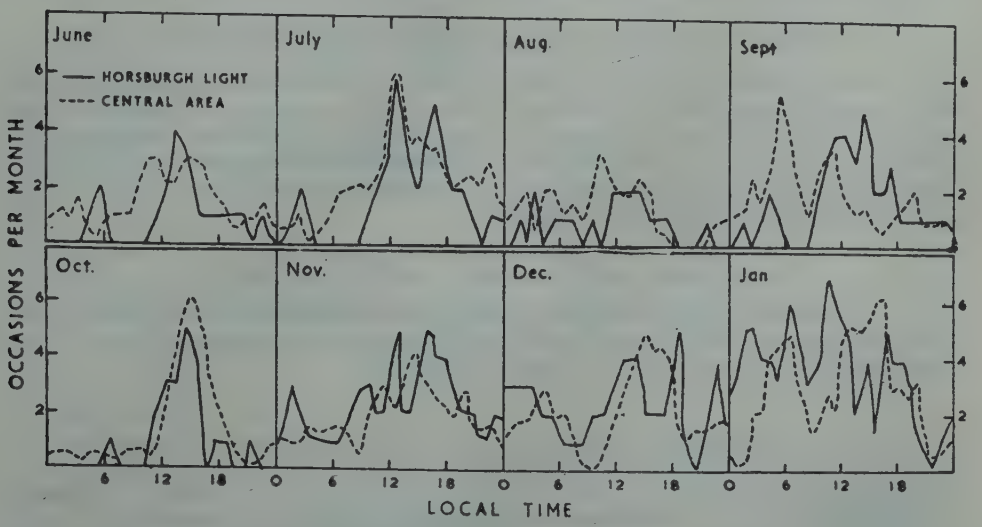

Fig. 16. Diurnal variation of rain over sea and over land for 1953.

Horsburgh with that over Central Singapore during the period June 1953-January 1954. This show that the peaks of maximum frequency occur at much the same times at both places, which is rather at variance with Braak's[1] finding that rainfall at Discovery Oostbank[2] occurred mostly between 5 a.m. and 2 p.m. A morning peak was found at Horsburgh in all months, but it was not nearly so prominent as that of Central Singapore in September. While morning precipitation over Singapore in the South-West Monsoon is due to the local effect extending all over the west coast of Malaya[3], the early morning rain at Horsburgh may have a different cause and is possibly brought about by instability following radiational cooling of cumuliform cloud-tops.

An afternoon peak of frequencies occurred each month (June 1953 to January 1954) at Horsburgh and was very similar to conditions over the land. It might be due to cumulonimbus forming in Johore and moving across the Lighthouse, but Horsburgh is eight miles from Johore and the peak is present even in months when the general wind prohibited such movement. The rock on which Horsburgh Lighthouse stands is about 20 or 30 yards square so that its diurnal variation of temperature should not influence cumuliform growth. It is possible, however, that there is a diurnal temperature variation in the waters surrounding Horsburgh which have an average depth of only 6-10 fathoms. Such a temperature variation could affect afternoon cumuliform activity. An investigation was commenced in 1954 to determine whether there is a diurnal variation of sea temperature near Horsburgh. At the same time an investigation was commenced to determine whether Raffles Light and Sultan Shoal have a diurnal variation of precipitation similar to that at Horsburgh.

1. C. Braak, "Diurnal Variation of Rainfall at Sea," *Het Klimaat van Nederlandsch-Indie*, Deel 1, Aflevering 8 (Batavia, 1925), p. 255.
2. Discovery Oostbank is a small reef between Borneo and Billiton.
3. Watts, *Equatorial Weather*, p. 70.

CHAPTER V

REPRESENTATIVENESS OF OBSERVATIONS.

Although the long-period monthly means of rainfall for different sites are similar over a large section of the island (Table 2), it was seen in Chapter III that there are sometimes large differences in the total falls at different stations over a period of a few days. This indicates the desirability of determining whether the records of a single gauge may be used to describe the daily and monthly rainfall within a few miles radius of that gauge.

(1) DAILY AND MONTHLY TOTAL RAINFALL

Table 6 shows the differences as observed (for the six months January-June 1953) between the daily falls at Paya Lebar Works Office and those at Paya Lebar Police Station, which is only a mile and a half away.

TABLE 6: COMPARISON OF PAYA LEBAR AND P.W.D. GAUGE RECORDINGS

24-HOUR RAINFALL P.W.D. PAYA LEBAR (INCHES)	DIFFERENCES BETWEEN P.W.D. GAUGE AND PAYA LEBAR POLICE STATION GAUGE (IN.)							
	0-0.25	0.26-0.50	0.51-0.75	0.76-1.00	1.01-1.25	1.26-1.50	1.51-1.75	1.76-2.00
0·01-0·50	65	11	1	—	1	1	—	—
0·51-1·00	6	4	1	—	—	—	—	—
1·01-1·50	2	6	—	—	—	—	1	—
1·51-2·00	1	2	2	1	1	1	—	—
2·01-3·00	—	2	—	—	1	—	—	—

The entry '65' means that on 65 days the P.W.D. gauge recorded falls between 0·01 and 0·50 in, and at the same time the Police Station gauge differed from these by between 0 and 0·25 in.

This table shows that during a total of 181 days the falls at the two gauges differed by more than one inch on 6 occasions. Summarizing the differences as follows, it may be seen that heavier daily rainfall occurred at one or other of the gauges with nearly the same frequency.

P.W.D. 24-hour fall	>	Police Station 24-hour fall	— 58 occasions
" " " "	<	" " " " "	— 45 "
" " " "	=	" " " " "	— 7 "
Both recording nil			— 71 "

Large differences may be found even between the monthly totals at adjacent places. Table 7 shows the corrections which would need to be applied to the actual monthly totals (January-June 1953) at (i) Lim Chu Kang and the Naval Base to give the rainfall as measured at Woodlands, and (ii) P.W.D., Paya Lebar to give the rainfall as measured at Paya Lebar Station.

TABLE 7: CORRELATION OF RECORDINGS AT SELECTED STATIONS

Stations used	Corrections to Give Woodlands Actual Total (Based on 1953 recordings)					
	Jan.	Feb.	Mar.	Apr.	May	Jun.
Lim Chu Kang (4½ mls. away)	+ 4%	+ 72%	+ 5%	— 51%	— 1%	— 9%
Naval Base (3 mls. away)	— 6%	+ 22%	— 10%	+ 17%	— 19%	— 66%
Mean of Naval Base and Lim Chu Kang	— 8%	+ 43%	— 3%	— 31%	— 10%	— 50%
	Correction to Give Paya Lebar Police Station Actual Total. (Based on 1953 recordings)					
P.W.D. Paya Lebar (1½mls. away)	+ 12%	— 19%	— 9%	— 11%	— 7%	— 33%

The daily or monthly catch of a gauge thus gives no reliable indication of the fall at a place only one and a half miles away. Daily rainfall figures for Kallang Airport and No. 9 Gate Singapore Harbour Board are sometimes quoted in insurance claims and legal disputes regarding other parts of the island but their validity has to be doubted.

TABLE 8: MEAN NUMBER OF RAIN-DAYS, SINGAPORE, FROM RECORDS OF A SINGLE GAUGE

Month	J	F	M	A	M	J	J	A	S	O	N	D	Year
Rain Days (0·01 in. or more)	16	11	15	15	14	14	13	15	14	16	18	19	180

The large differences in daily or monthly falls are brought about by the small horizontal area and short life of individual storms together with the great intensity of rainfall in them (see half-hourly isohyetes for 21/1/53, 1/12/53 and 21/7/53 in Figs. 20, 30 and 27. Fig. 17 shows the maximum intensities recorded in Singapore in ten years (1931-1940)[1]. The falls of 4·73 in. in one hour and 5·79 in. in two hours were probably local and would obviously have a large influence on the daily and monthly totals.

The extreme intensities at Singapore are similar to extremes recorded in the Federation of Malaya though rather less than some maximum intensities recorded in other parts of the world[2] (Fig. 17).

1. The greatest fall recorded at Singapore up to February 1955 are as follows:

Hours	¼	½	¾	1	2	3	4	5	6	12	24	48	72	96	120	144	168
Inches	1.67	3.15	4.13	4.73	5.79	5.84	5.84	5.84	6.23	8.89	12.90	13.78	15.20	15.71	15.71	15.71	16.50

2. "Thunderstorm Rainfall," *Hydrometrical Report No. 5, U.S. Dept. of Commerce, Weather Bureau and U.S. War Dept., Part II* (Vicksberg, Waterways Experiment Station, 1947), Fig. 142.

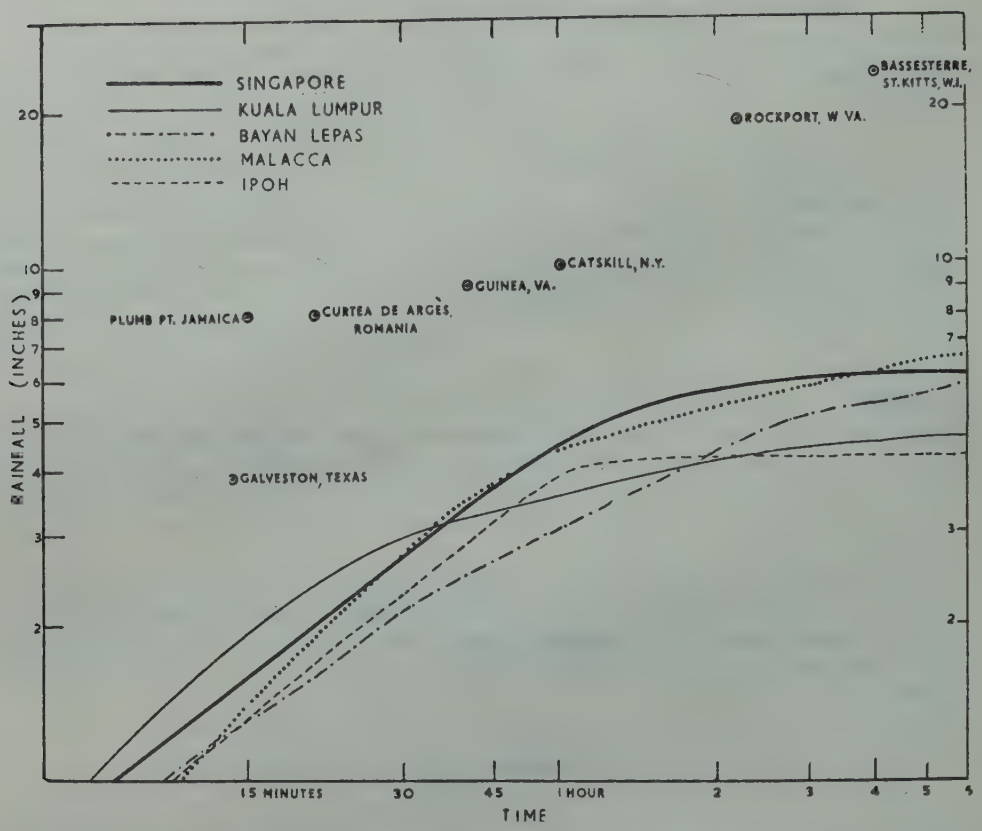

Fig. 17. Maximum observed rainfall intensities.

(2) RAIN-DAYS PER MONTH

It has been shown in the previous section that it is not possible to assess the daily or monthly rainfall at any place by the rainfall recorded at a neighbouring gauge. Similarly, it cannot be assumed that there has been any rain at a place on a certain day merely because an adjacent gauge has recorded rain. This does not preclude the possibility that the number of rain-days per month over the island might be represented adequately by the records of a number of stations.

Rain-days per month are usually described as the number of days on which a single gauge collects 0·01 of an inch or more of rain. Thus, Table 8 gives the official values of mean monthly and annual rain-days computed from eighty-two years' observations (1869-1950) of a single gauge sited successively at Convict Prison, Kandang Kerbau, Mt. Faber, Botanical Gardens and Kallang Airport.

Although it would appear from Table 8 that rain falls on about fifteen days per month, it is likely that rain falls somewhere on the island (as distinct from

the fall at a single gauge) with much higher frequency. The reason for this difference is that many storms are of small horizontal extent (see Chapter VI and half-hourly isohyets for 22/1/53 in Fig. 20).

It can be shown as follows that five properly distributed gauges are required to record the number of days when there is measurable rain on the island in any month. Fig. 18 shows the number of rain-days recorded when different numbers of gauges are taken as representative of the whole island. Using only the MacRitchie gauge, 60 per cent of days (during January-April 1953) are rain-days. Supposing that rain falling in any one of three gauges (Kallang, Tengah and Yio Chu Kang) marks a rain-day, then 83 per cent of the days are rain-days. With five gauges — MacRitchie, Lim Chu Kang, Pulau Seraya, Kampong Bahru (Pulu Ubin) and Joo Chiat—88 per cent are rain-days. With ten gauges (as for five above, plus Pasir Laba, Bukit Panjang, Sĕmbawang, Changi Gaol and Harbour Board No. 9 Gate) the percentage increases only to 89, and the increases in number of rain-days are small when the number of gauges is further increased.

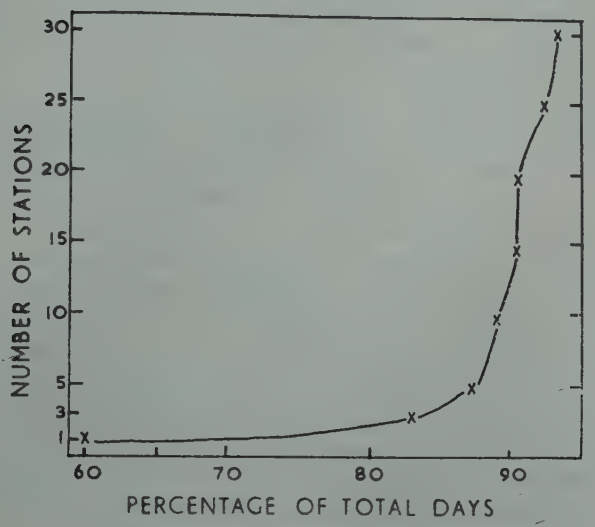

Fig. 18. Singapore: rain-days as a percentage of total days from January to April, 1953, as determined from varying numbers of gauges.

From the foregoing it follows that any computations of dry spells from the records of a single gauge are unrepresentative of conditions over the whole Island. Low[1] has stated that a drought of six weeks' duration is rare in Singapore, while Davidson[2] has claimed that, during eighteen years, no rainless period lasted longer than three weeks. Official rainfall records for a single gauge (in four successive sites) show that in fifty-eight years the longest dry spell was of only thirty days' duration and there were only ten dry spells of duration more than seventeen days (Fig. 19). If these dry spells had been computed from the five gauges necessary

1. James Low, "Extracts from an Unpublished Journal of a Residence at Singapore during part of 1840 and '41", *Singapore Free Press*, November, 1841.
2. G.F. Davidson, *Trade and Travel in the Far East* (London, 1846), p. 40.

to define rain-days and had thus been representative of the whole Island, they would presumably have been of shorter duration and less frequent.

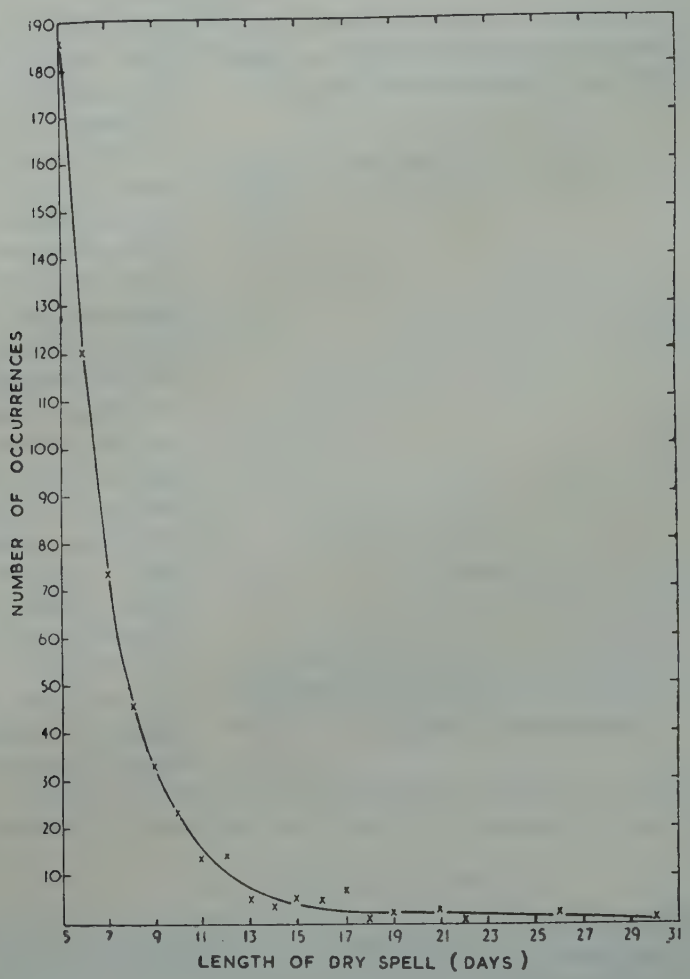

Fig. 19. Singapore: number of dry spells in fifty-eight years (1882-1939).

CHAPTER VI

FORM AND MOVEMENT OF DISCRETE ISOHYETAL PATTERNS

(1) ISOHYETAL PATTERNS

During 1953 isohyets have been drawn for each exact half-hour L.T. in order to examine the rainfall patterns of storms over Singapore. The isohyets have the following values: 0·05, 0·10, 0·20, 0·30, 0·50, 0·70, 1·00, 1·50, 2·00, 2·50, and 3·00 inches. As the automatic gauges were spaced from two to six miles apart, only the larger storms could be considered. Therefore, isohyets have been drawn only for occasions when (i) more than twenty-four gauges (out of a total of twenty-nine) had rain in a three-hour period; (ii) at least one of the gauges recorded intense rain. The minimum intensity accepted was one inch per half-hour.

These criteria were adopted arbitrarily in order to exclude cases of widespread light rain from altostratus, storms of small horizontal extent and those which only touched on the fringe of the Island. It was found that the examples chosen by using the two criteria included every instance of intense rain except where it occurred on the edge of the network.

Selected isohyetal patterns are shown in Figs. 20-30 (These are arranged according to date although reference has been made to some of the Figs. in earlier chapters). In drawing the isohyets it has been assumed that the intensity of rainfall varies uniformly between any two stations of the network. While this assumption may seem fallacious in the light of the findings of Chapter V, the Singapore distribution of gauges—one per six square miles—is comparable with the network used by Boerema[1] for a similar investigation in Batavia on the basis of one gauge per five square miles. Furthermore, the records of a dense network of one gauge per two square miles used in Singapore City for a separate investigation during 1954 show that, where a gauge has recorded one inch or more in half an hour, the isohyetal patterns are at least six miles wide.

In drawing the isohyets, it has also been assumed that storms are approximately circular (after the pattern of a Benard cell) with heaviest rainfall at the centre. This was found practicable because, even when the isohyetal patterns of two or more centres merged, the separate circular shape of each was usually distinguishable.

To test whether one set of observations could be interpreted in different ways, three meteorological analysts skilled in drawing isopleths, were separately asked to draw isohyets for a given series of observations. The analyses were all similar to those shown here. Different interpretations arose only regarding whether, in places where one station had rain and an adjacent one had none, the isohyets should be closely packed near the former or should extend near to the latter station. A compromise has been effected in such cases and the isohyets extrapolated towards the rainless station with the same spacing used in those parts of the same storm where several stations recorded rain. The patterns formed thus are fairly representative of actual conditions, since they are similar to those drawn for storms where records of 0·01 in. to 0·04 in. per half-hour are available to fix the outermost isohyet.

1. J. Boerema, "Uitbreiding van Regenbuien te Batavia," *Koninklijk Magnetisch en* Meteorologisch Observatorium te Batavia, Verhandelingen No. 15, (1925), pp. 20-21.

(2) DIAMETER OF STORMS

It is not easy to determine the form of all storms because many are complex, consisting of several centres with merging isohyetal patterns (see half-hourly patterns for 20/2/53 in Fig. 22). Where separate centres have been determined, the half-hourly maps show great variations in diameter. Many isohyetal patterns are elliptical with longer axes of 12-22 miles, and this is thought to result from a small movement of a circular storm within the half-hour (See half-hourly isohyets for 20/5/53 in Fig. 25). Therefore, the smaller axis has been taken to represent the instantaneous diameter of a circular storm. Most diameters were six miles or less (see half-hourly isohyets for 5/11/53 in Fig. 29), although four examples have been found with diameters as great as eleven miles.

Hay[1] states that radar-wind observations indicate the height of the tropopause over Singapore to be approximately 55,000 ft., above which westerlies replace the easterlies of the troposphere. If convection extends to this height and a storm is similar to a Benard cell, then the width of the cell would be 36 miles; the diameter of the cloud would be 18 miles and that of the isohyetal pattern 13½ miles. As diameters of this size were not found in isolated cells, it appears that convection usually ceases below 55,000 ft. and that the wind-shear found by Hay may not in fact occur at the tropopause. This could only be determined by radiosonde data which were not available in 1953.

(3) MOVEMENT OF STORMS

The short life of individual storms makes it difficult to assess their movement on the basis of half-hourly isohyetal maps, but it is not reasonable to draw maps for shorter periods because of possible errors in the rain-gauge clocks and in the setting of the charts. Amalgamation of two or more centres also makes it difficult to assess movement. At times there was a general development of the rain-pattern down-wind, though no movement of the separate centres was distinguishable (see half-hourly isohyets for 28/1/53 in Fig. 21).

The movement of a storm from one half-hourly map to the next has been detected on forty occasions (e.g., isohyets for 21/3/53 in Fig. 24), while storms remained stationary from one map to the next on twelve occasions. For the occasions when there was definite movement, Table 9 compares the direction of movement with the upper-wind direction shown by Kallang pilot-balloon observations at 07.00 hours L.T.

TABLE 9: COMPARISON OF DIRECTIONS OF UPPER WINDS AND DIRECTION OF MOVEMENT OF STORMS

Height of Upper-wind Observation	Angle between upper-wind and direction of movement of storm-centre.			
	(A) 0-30°	(B) 0-60°	(C) 61-120°	(D) 121-180°
3,000 ft.	37	65	20	15
5,000 ft.	43	63	27	10
7,000 ft.	34	59	24	17
10,000 ft.	28	50	38	12
15,000 ft.	33	55	28	17
20,000 ft.	22	56	33	11

1. R.F.M. Hay, "High-level Easterlies over Singapore and Hong Kong", *Weather*, Vol. 8, No. 7, (London, 1953), p. 207.

The first analysis [column (a) of Table 9] gives the number of occasions when the direction of movement was very close to the wind direction (i.e. within 0° to 30° of it). This relation was sustained in only 22-43 per cent of all the cases in which movement was recognized. As it is possible that errors have been made in assessing the direction of movement, a larger tolerance was tested and column (b) shows that the direction of movement was within 0° to 60° of the observed wind on 50-65 per cent of the occasions. Even then it appears that the number of occasions when the centres moved approximately down-wind are not greatly in excess of the total of occasions when they moved across-wind and up-wind [columns (c) and (d)].

These findings with regard to Table 9 do not preclude the possibility that down-wind movement may be associated with only the stronger winds. To test this, Table 10 has been prepared, including only those occasions when the direction of movement was within 30° of the observed winds.

TABLE 10: DISTRIBUTION OF UPPER-WIND SPEEDS WHEN MOVEMENT OF STORM WAS WITHIN 30° OF UPPER-WIND DIRECTION

Height of Upper-wind Observation	Upper-wind speed (m.p.h.)			No. of Observations
	0-10	11-20	> 20	
3,000 ft.	4	4	8	16
5,000 ft.	7	8	2	17
7,000 ft.	6	4	2	12
10,000 ft.	5	4	—	9

This table shows the number of occasions when down-wind movement was associated with various ranges of wind-speed. From the table it may be seen that down-wind movement does not depend on the wind-speed at 5,000, 7,000 or 10,000 ft. It might be assumed that some critical wind-speed at 3,000 ft. causes movement, since there were twelve occasions when that wind exceeded 10 m.p.h. but only four occasions when it was lighter. That this assumption is unjustified may be deduced from Table 11, which gives the number of occasions when different wind-speeds occurred in association with storms which remained stationary from one half-hourly map to the next.

Here are six occasions of light winds at 3,000 ft. and an equal number of winds over 10 m.p.h., which shows that the 3000-ft. wind-speed does not necessarily influence the movement.

TABLE 11: DISTRIBUTION OF UPPER-WIND SPEEDS WHEN STORM WAS STATIONARY

Height of Upper-wind Observation	Upper-wind speed (m.p.h.)			No. of Observations
	0-10	11-20	> 20	
3,000 ft.	6	6	—	12
5,000 ft.	10	2	—	12
7,000 ft.	10	2	—	12
10,000 ft.	10	2	—	12

It may be noted that the stationary storms (Table 11) are much more frequently associated with light winds than with stronger winds in the 5,000 to 10,000-ft. layer. This cannot be considered significant because Table 10 showed that the movement of storms does not depend on the wind-speed at 5,000 to 10,000 ft.

Fig. 20. Singapore: half-hourly isohyets for 22/1/53. Showing that the diameter of a storm may be so small that the total number of rain-days recorded by a single gauge is not representative of the whole Island. Upper winds at Kallang at 07.30 hours L.T. were:

3,000 ft.	020°/05 knots	7,000 ft.	340°/05 knots
5,000 ft.	350°/15 knots	10,000 ft.	350°/05 knots

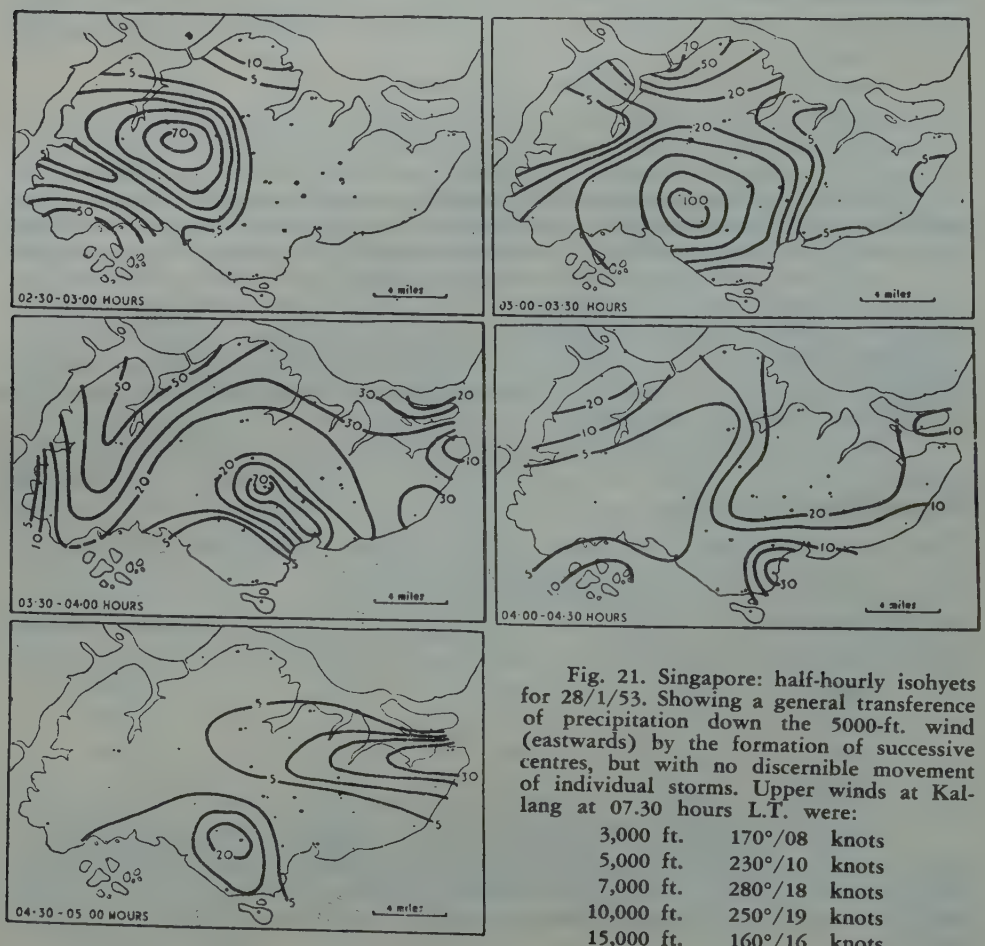

Fig. 21. Singapore: half-hourly isohyets for 28/1/53. Showing a general transference of precipitation down the 5000-ft. wind (eastwards) by the formation of successive centres, but with no discernible movement of individual storms. Upper winds at Kallang at 07.30 hours L.T. were:

3,000 ft.	170°/08 knots
5,000 ft.	230°/10 knots
7,000 ft.	280°/18 knots
10,000 ft.	250°/19 knots
15,000 ft.	160°/16 knots

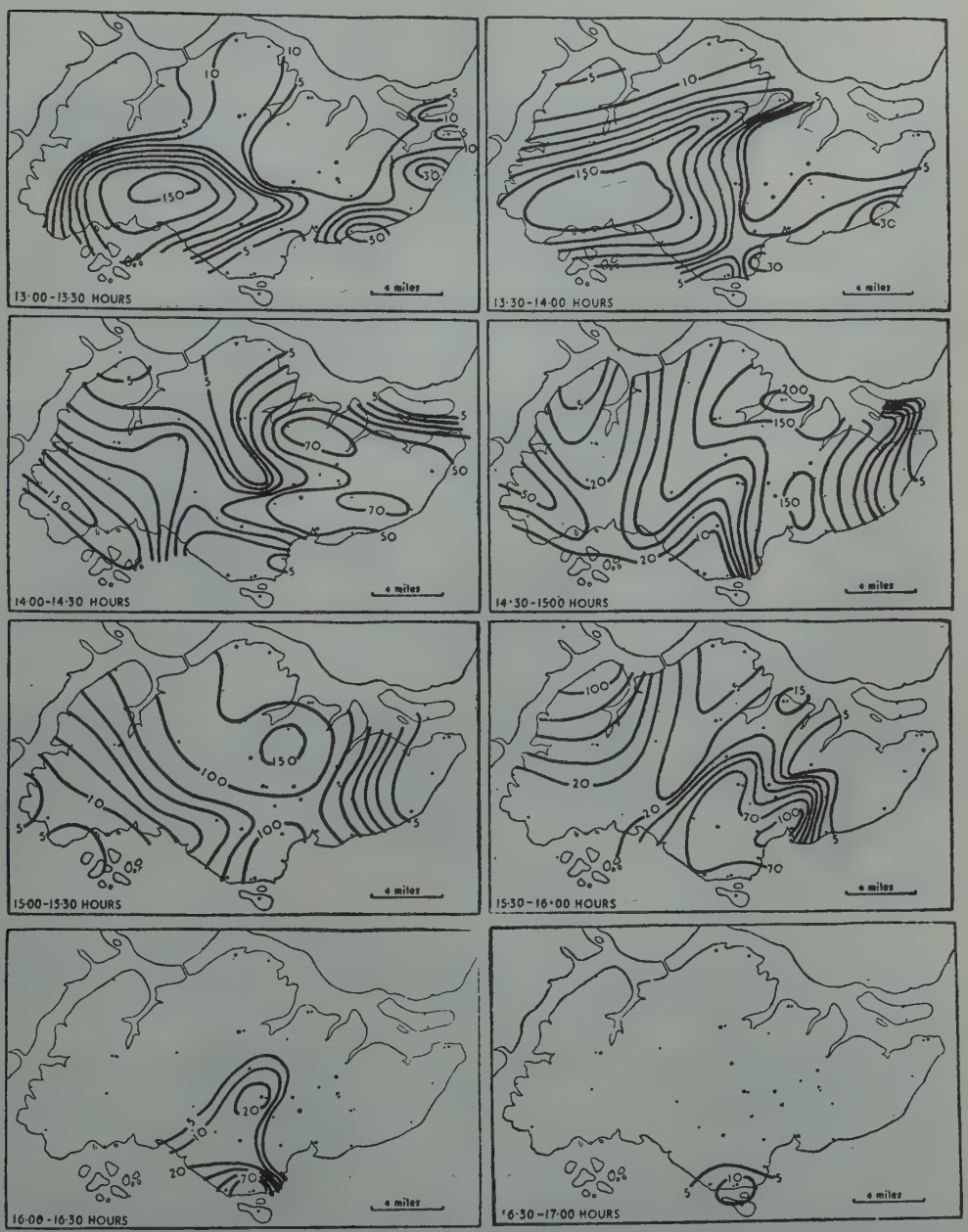

Fig. 22. Singapore: half-hourly isohyets for 20/2/53. A large storm consisting of several intense centres with no discernible movement and covering nearly all the Island at some time within a period of three hours. Upper winds at Kallang at 07.30 hours L.T. were:

3,000 ft.	070°/13 knots	10,000 ft.	120°/11 knots
5,000 ft.	090°/13 knots	15,000 ft.	100°/09 knots
7,000 ft.	120°/10 knots		

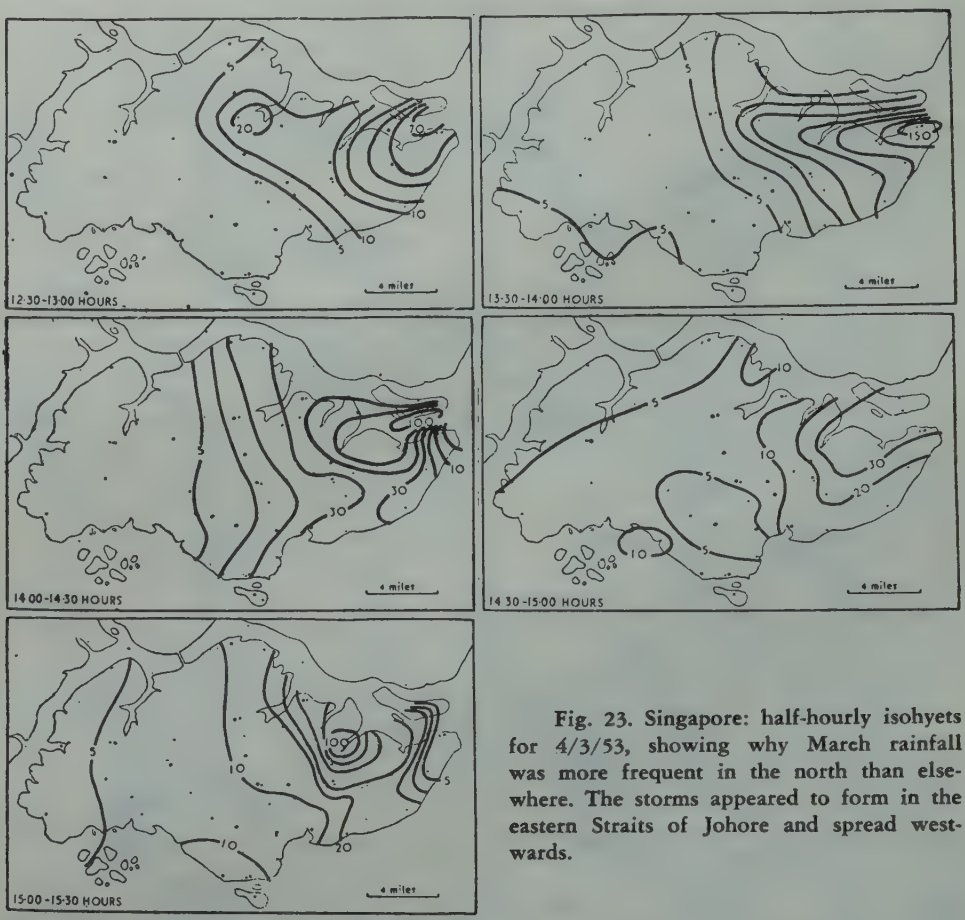

Fig. 23. Singapore: half-hourly isohyets for 4/3/53, showing why March rainfall was more frequent in the north than elsewhere. The storms appeared to form in the eastern Straits of Johore and spread westwards.

The distances moved by the centres of individual storms from one half-hourly map to the next are shown in Table 12.

TABLE 12: DISTANCE TRAVELLED BY STORMS FROM ONE HALF-HOURLY MAP TO THE NEXT.

DISTANCE TRAVELLED (MLS.)	1-3	4-6	7-8	TOTAL
No. OF STORMS	12	18	1	31

Nearly all centres travelled 6 miles or less, and if the average time of travel is presumed to be half an hour (from the middle of one half-hour period to the middle of the next), their average speed was 8 m.p.h. This is rather less than the wind-speed (12 m.p.h. at 5,000 ft.) averaged for those occasions when distance of travel was measured for inclusion in Table 12.

The half-hourly isohyetal maps show that in general the movement of storms is not related to the upper wind and that at one time two storms can even move in different directions (See half-hourly isohyets for 30/8/53 in Fig. 28). It appears likely that many apparent movements were due to a second storm being induced

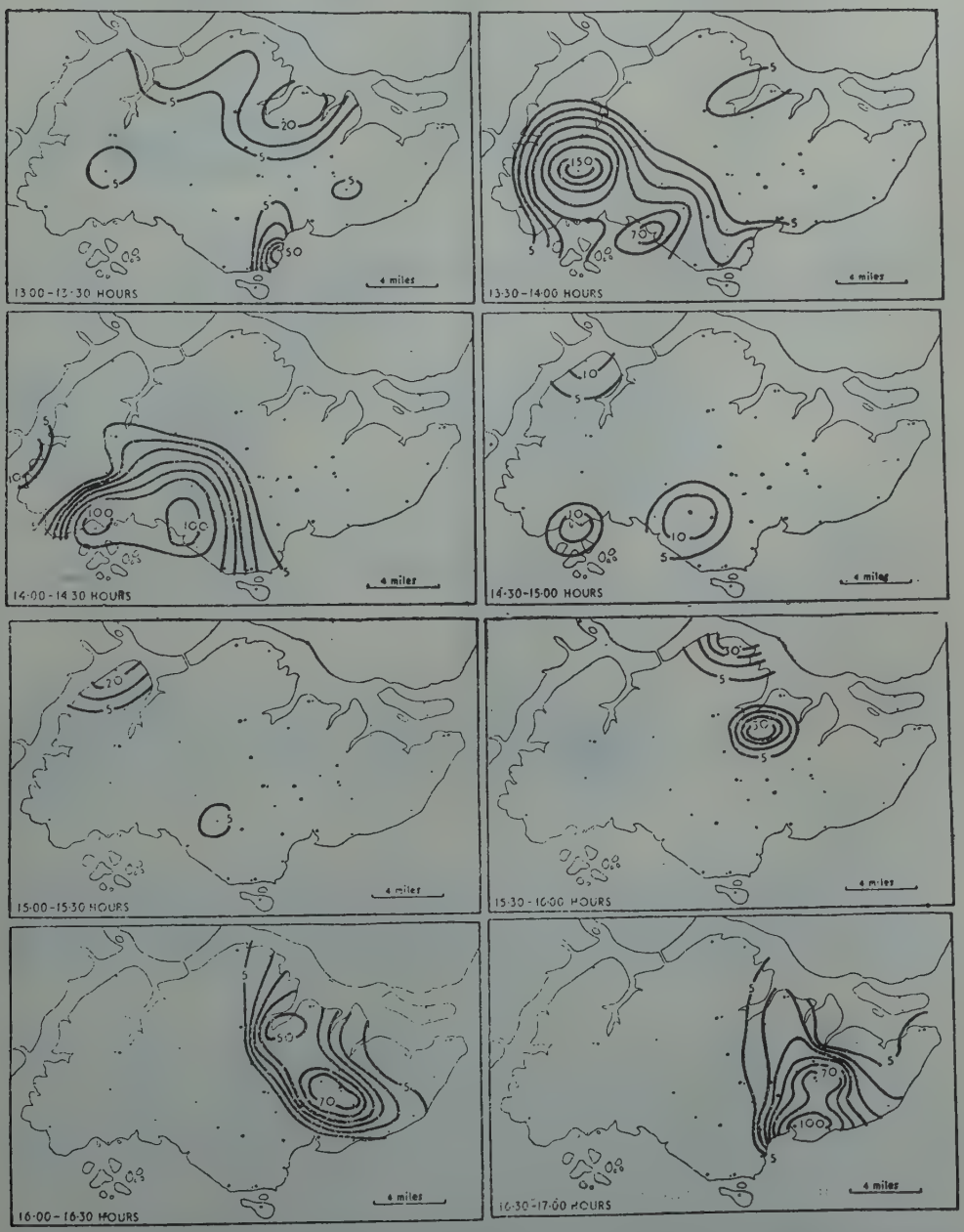

Fig. 24. Singapore: half-hourly isohyets for 21/3/53. Storms in March were not confined to the north but formed haphazardly anywhere on the Island. Probable movements on the 21st. were (i) Jurong to Tanjong Kling, 3 miles to the south, in less than one hour. (ii) Yio Chu Kang to P.W.D. Paya Lebar, 4½ miles, in less than one hour. (iii) P.W.D. Paya Lebar to Joo Chiat, 3½ miles to the south, in less than one hour. Upper winds at Kallang at 07.30 hours L.T. were:

3,000 ft.	030°/22 knots	7,000 ft.	010°/09 knots
5,000 ft.	010°/05 knots	10,000 ft.	280°/08 knots

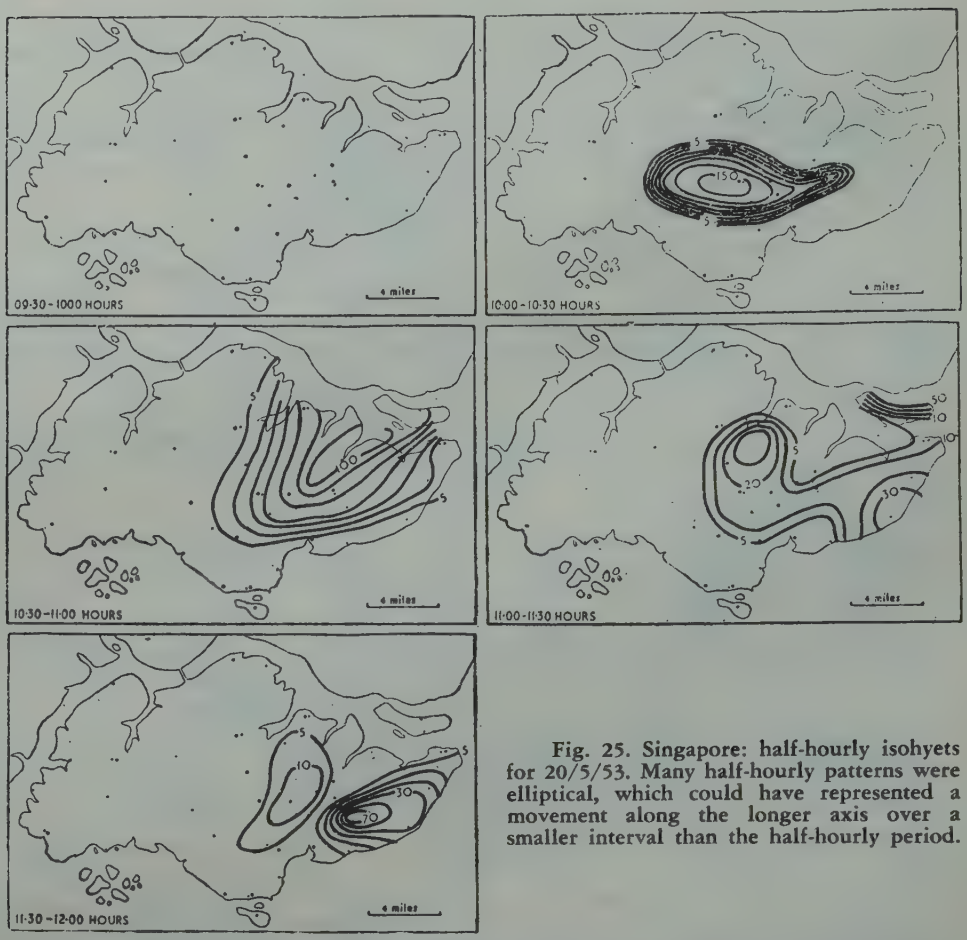

Fig. 25. Singapore: half-hourly isohyets for 20/5/53. Many half-hourly patterns were elliptical, which could have represented a movement along the longer axis over a smaller interval than the half-hourly period.

by the downdraft associated with an existing cumulonimbus as described by Byers[1] (see isohyets for 14/7/53 in Fig. 26). Since it is still possible that storms move with the upper-wind over intervals of time of less than a half-hour, a separate long-period investigation was commenced in 1954, using a denser network.

(4) DURATION OF STORMS

An assessment has been made of the length of life of the larger discrete storms during 1953 (i.e., of all the discrete storms during periods when more than twenty-four of the 29 gauges recorded rain and at least one gauge had one inch or more in half an hour). The duration of a storm has been estimated by identifying it on successive half-hourly maps. In this way the moving storms are also included, so that the analysis gives a better picture of the life of the storms than could be obtained by analysing the duration of rainfall at a single station.

It is found that most storms maintained their separate existence for periods up to one hour (see half-hourly isohyets for 21/7/53 and 1/12/53 in Figs. 27 and 30). The number of these short-lived storms would have been greatly increased if isohyets had been drawn for the whole year instead of only for the periods selected by the criteria described above.

1. H.R. Byers, "Structure and Dynamics of the Thunderstorm," *Weather*, Vol. 4, No. 8 (1949), pp. 249-50.

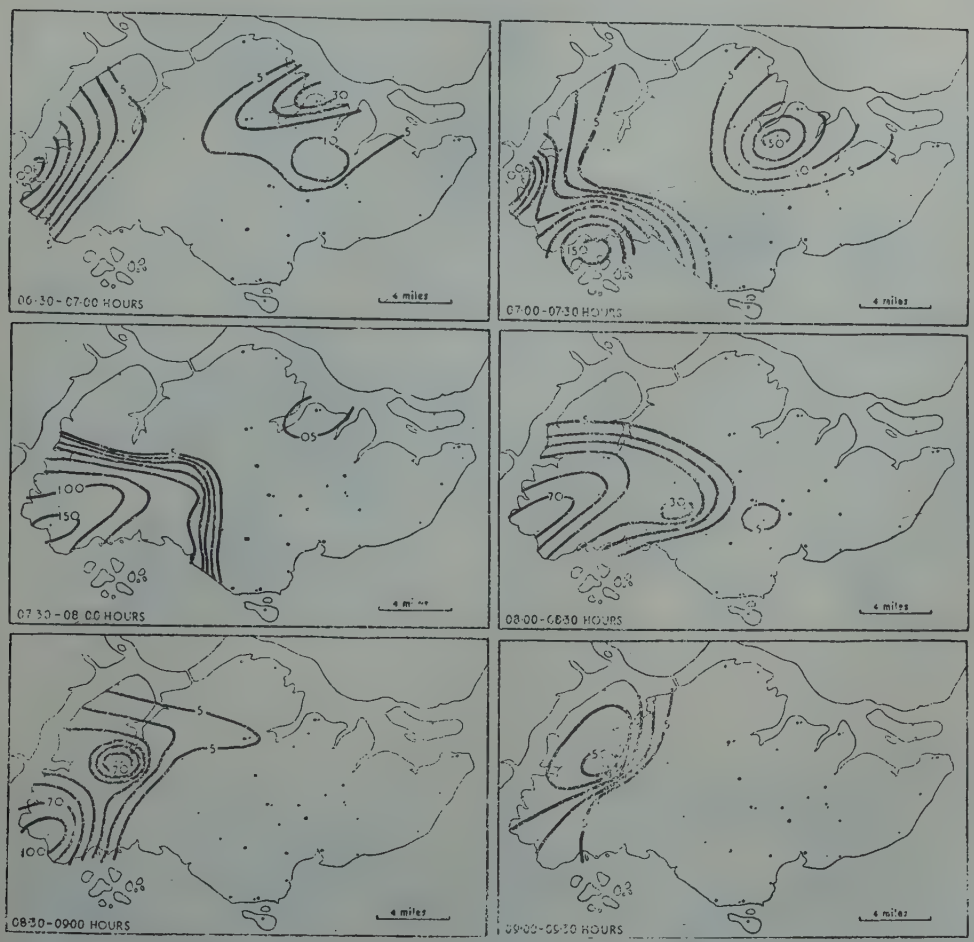

Fig. 26. Singapore: half-hourly isohyets for 14/7/53. Early morning storms in July did not usually extend over the Island. The storm over Pasir Laba possibly induced another at Tanjong Kling (five miles to the south-east), and the two merged over Tuas. Thus, rain over that area lasted for three hours, but any one station had rain for only two hours at the most.

The number of occasions when the 1953 isohyets showed storms lasting more than one hour are shown in Table 13.

TABLE 13: NUMBER OF STORMS OF DIFFERENT DURATIONS, 1953.

LIFE (HOURS)	> 1	> 1 ½	> 2	> 2 ½	> 3	> 3 ½	> 4	> 4 ½	> 5	> 5 ½ - 6
NO. OF STORMS	45	19	5	3	3	3	1	1	1	1

It is likely that there were some hundreds of storms lasting one hour or less. Table 13 shows forty-five lasting more than one hour but only five of these lasting more than two hours. The longest duration was six hours.

Although rainfall-rates are sometimes very high (Fig. 17) and the individual centres have little movement, severe flooding on the Island is infrequent. It seems that this is due to the compensation afforded by the short life and small horizontal extent of the storms.

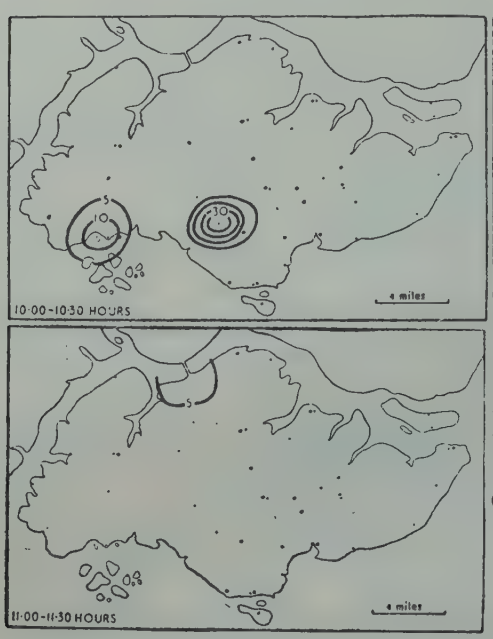

Fig. 27. Singapore: half-hourly isohyets for 21/7/53. Showing the short life and high intensity of rainfall in storms. In this instance an altostratus layer probably persisted, since there was scattered light rain from 11.00 to 12.00 hours, L.T. Upper winds at Kallang at 07.30 hours L.T. were:

3,000 ft.	190°/14	knots
5,000 ft.	210°/10	knots
7,000 ft.	230°/13	knots
10,000 ft.	260°/14	knots

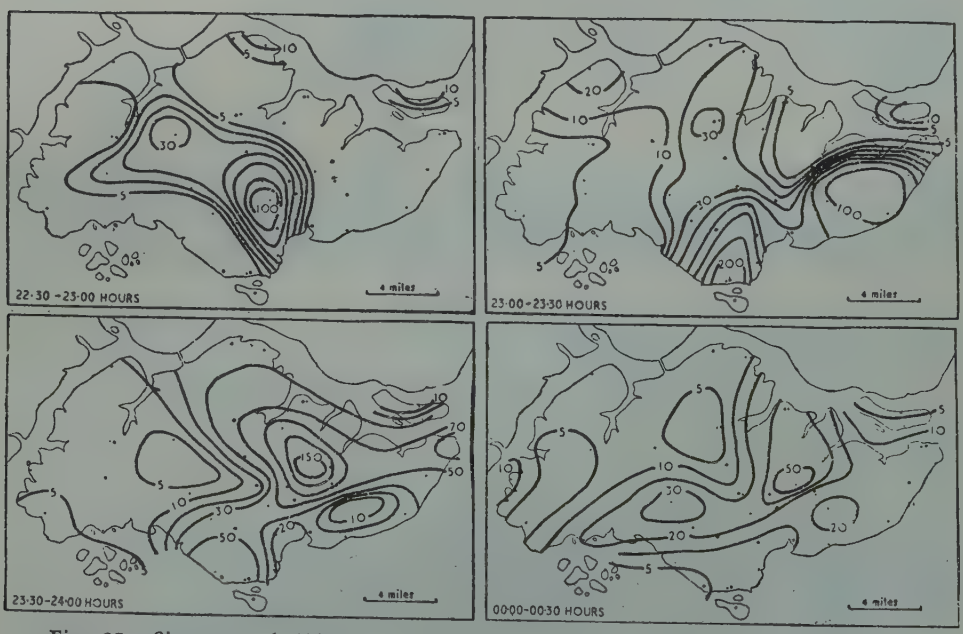

Fig. 28. Singapore: half-hourly isohyets for 30-31/8/53. Here two separate storms travelled in different directions at practically the same time (This situation is discussed in Chapters VI and VII).

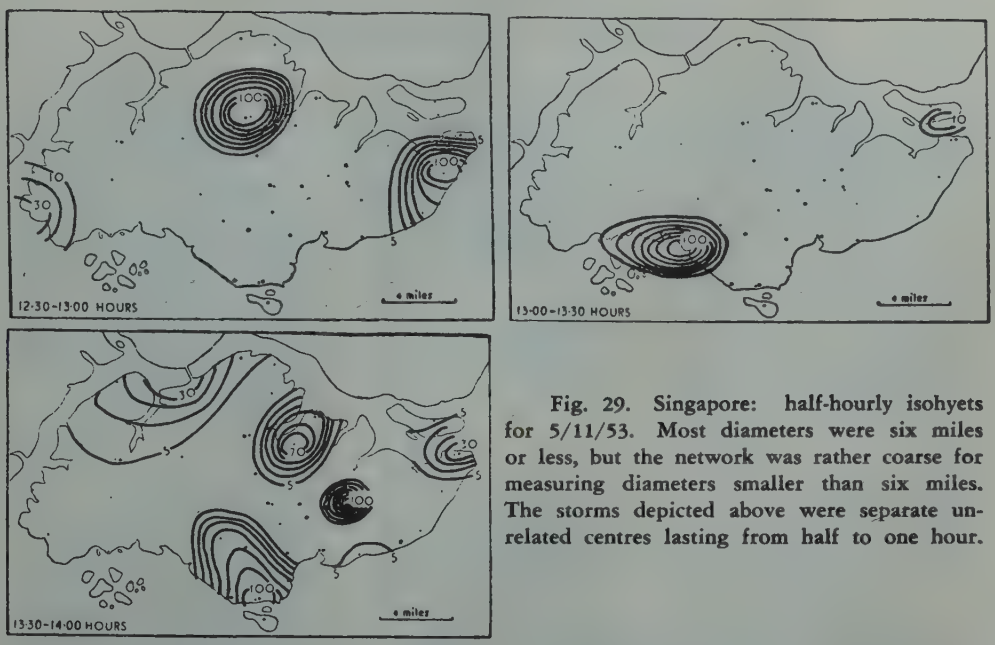

Fig. 29. Singapore: half-hourly isohyets for 5/11/53. Most diameters were six miles or less, but the network was rather coarse for measuring diameters smaller than six miles. The storms depicted above were separate unrelated centres lasting from half to one hour.

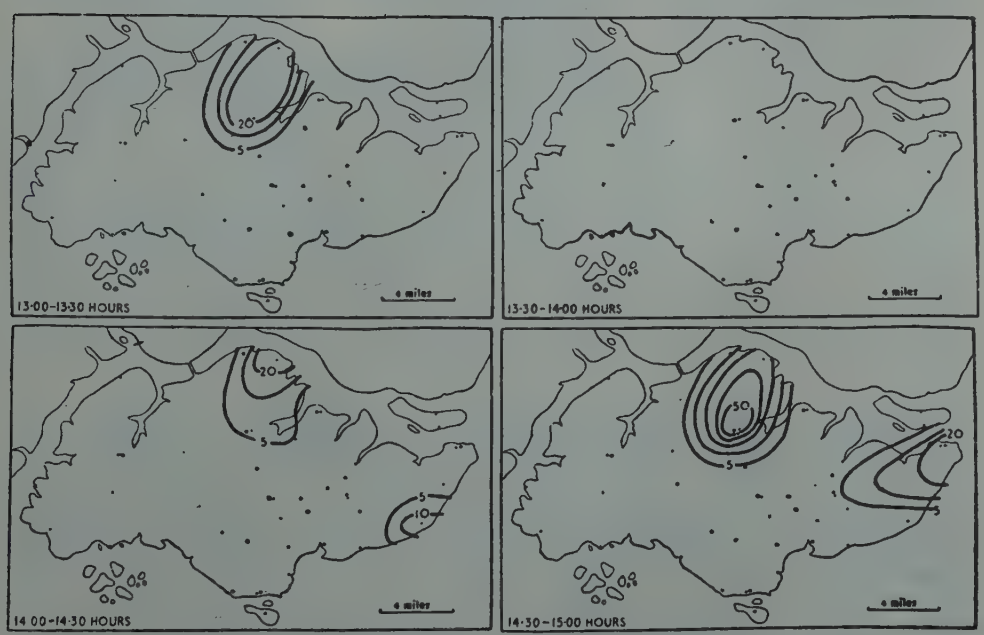

Fig. 30. Singapore: half-hourly isohyets for 1/12/53. Showing the short life of storms and how a centre may die and later be renewed in the same place.

CHAPTER VII

VARIETIES OF RAINSTORM

In Chapter VI only the discrete rainstorms were considered, but there are many occasions when merging isohyetal patterns denote large composite storms. A measure of the distribution of size of rainstorms may be obtained by considering the percentage of days on which rain is recorded by varying numbers of gauges on the Island. Fig. 31 shows that although there are many days on which various gauges record rain, there is a fairly high frequency (19 per cent) of days on which all twenty-nine gauges have rain. This suggests that rainfall is not always purely convective.

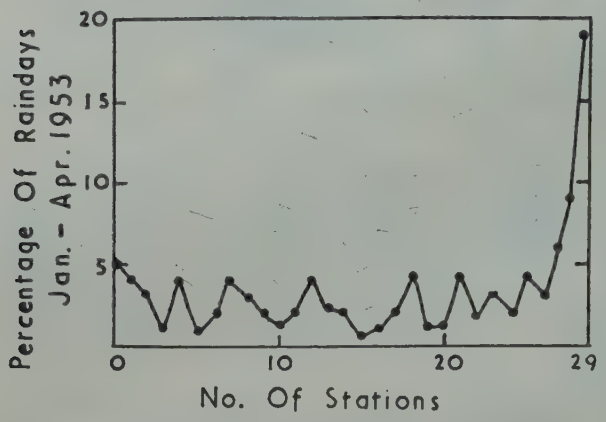

Fig. 31. Number of stations having rain on the same day.

There is considerable difference of opinion among meteorologists as to whether a form of 'frontal' synoptic weather-analysis is permissible at low latitudes. Garbell[1] and Forsdyke[2] employ frontal analysis at low latitudes in the same way as it is used in middle latitudes. As the temperature differences on which the frontal theory is based are not found near the Equator, it is doubtful whether the use of normal frontal methods is justified. Palmer[3] considers that no method even resembling frontal analysis should be employed in the tropics.

Watts[4] uses a form of analysis which recognizes air-stream boundaries between two air currents of different origin but similar properties. A series of separate or merging cumulonimbus clouds with rain are said to occur along or near these 'boundaries'. Watts[5] produces synoptic charts based on this theory, but the observing stations on the charts are too widely spaced to show the distribution of cloud along the boundary. From the network used, the boundary could consist of an unbroken cloud-belt or of a chain of separate storms, while it is not impossible that rain at any two stations along the boundary could be due to isolated convective cumuli. For that reason it is desirable to examine the Singapore network to determine whether there is such a condition as general rain over the Island and whether belts of rain or chains of storms are associated with air-stream boundaries.

1. M.A. Garbell, *Tropical and Equatorial Meteorology* (London, 1947).
2. A.G. Forsdyke, *Synoptic Analysis in the Western Indian Ocean* (East African Meteorological Service: Nairobi, 1948), pp. 1-11.
3. C.E. Palmer, "Tropical Meteorology", *Compendium of Meteorology: American Meteorological Society* (Boston, 1951), pp. 859-80.
4. I.E.M. Watts, *Equatorial Weather* (London, 1954).
5. Ibid.

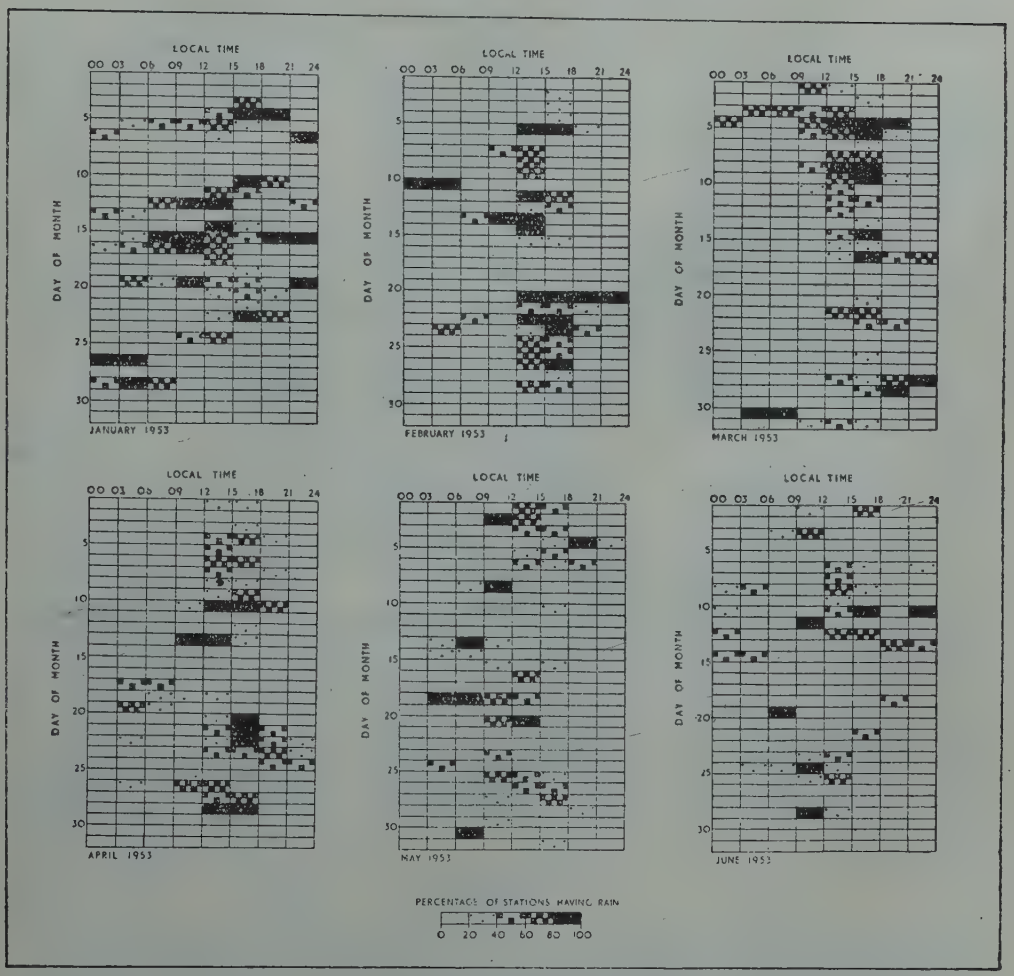

Fig. 32. Percentage of stations having rain in each three-hour period, January-June 1953.

(1) GENERAL RAIN

During 1953 there were at various times from twenty-eight to thirty-one recording gauges on Singapore and neighbouring small islands. On Fig. 32 has been plotted the percentage of gauges having rain in each three-hour period during the year. Thus between 15.00 and 18.00 hours L.T. on 3rd January, more than 60 per cent but less than 80 per cent of the gauges recorded rain. Figure 32 shows that although there were many periods of scattered precipitation, there were one hundred and thirty-two periods during the year when nearly all (80-100 per cent) stations recorded rain. This shows that periods of general rain are not uncommon and therefore rain is not always due to isolated convective cells; but it is still possible that the one hundred and thirty-two cases may include scattered light rain from altostratus. For that reason an examination has been made of the composite storms. The half-hourly isohyetal maps for widespread and intense rain (selected by criteria described on p. 43) are used for this examination.

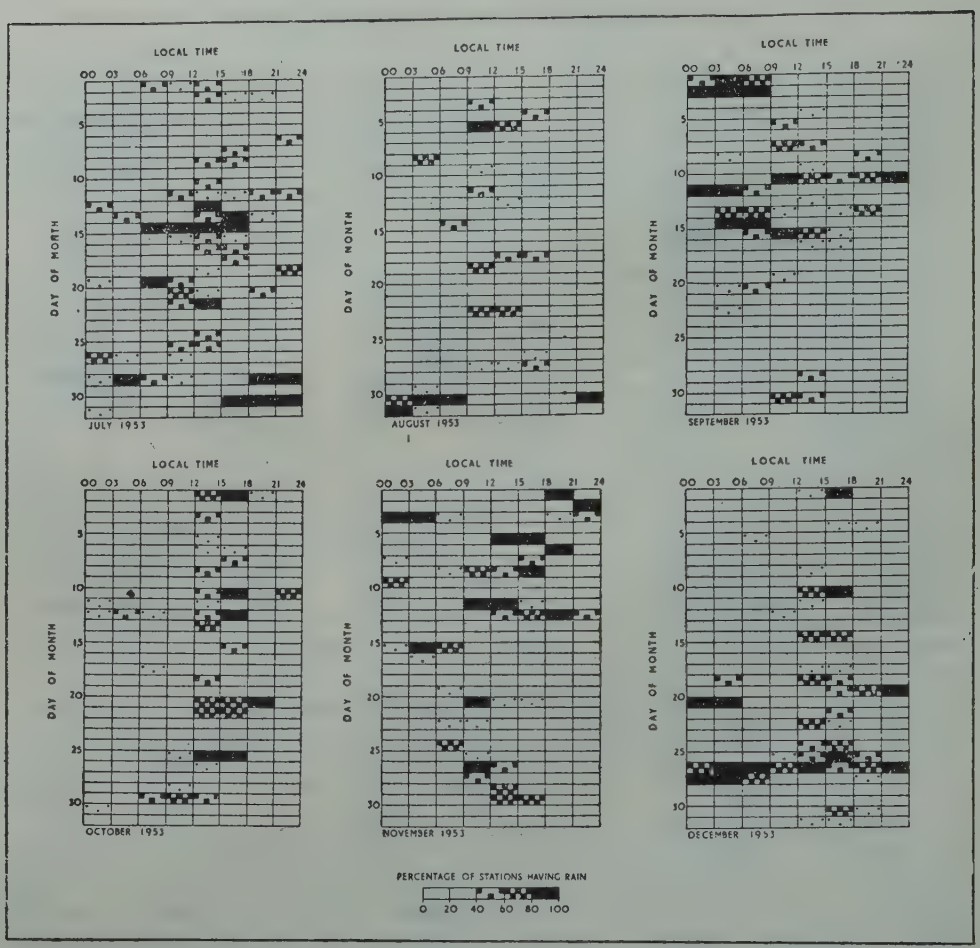

Fig. 32 (cont.). Percentage of stations having rain in each three-hour period, July-December, 1953.

(2) RAIN-BANDS

A few lines or bands of rain were detected (e.g. half-hourly isohyets for 10/1/53 and 5/8/53 in Figs. 33 and 34). These rain-bands were not associated with air-stream boundaries because they were not accompanied by marked changes of wind-direction. The passage of a rain-band on 10/1/53 was associated with a surge wholly within the North-East Monsoon current, because upper-winds (Fig. 35) show that a rather variable flow was replaced by north-easterlies at all levels.

Similarly, the rain-band of 5/8/53 passed across Singapore without any change in the upper south-westerly flow (Fig. 35) and, therefore, was not associated with an air-stream boundary.

(3) AIR-STREAM BOUNDARIES

Since the few rain-bands detected were not associated with air-stream boundaries, an examination has been made to determine what isohyetal patterns were

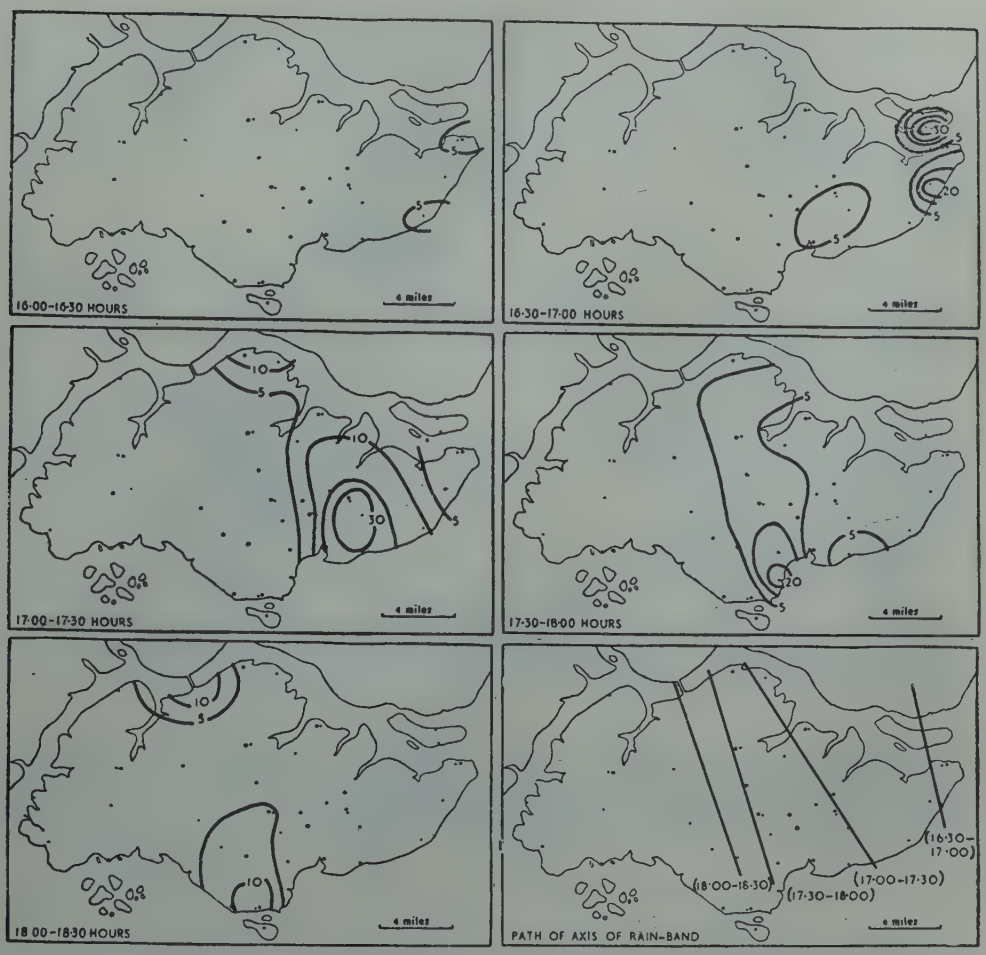

Fig. 33. Singapore: half-hourly isohyets for 10/1/53. A rain-band associated with a slight change of orientation within the North-East Monsoon (see upper-wind of Fig. 35). The rain-band was from 5 to 7 miles wide and moving WSW. at 4-8 m.p.h. The total life of the system was about two hours.

present with the passage of an air-stream boundary. Three occasions were found when the passage of a boundary with convergence over Singapore could be definitely established from the available upper-winds. On each of these occasions the isohyetal pattern was not in the form of a rain-band, but consisted of several intense storms, each about eight to eleven miles across and sometimes merging.

An example on 10/6/53 is shown in Fig. 36. With the passage of this boundary, southerlies at 3,000 to 5,000 ft. over Singapore at 07.30 hours L.T. on the 10th were replaced by northerlies before 16.30 hours L.T. (see Fig. 35).

The storms associated with the boundary-passage show several distinct centres, one of which had 3·15 in. of rain in half an hour and 4·66 in. in sixty minutes. Movement of the centres cannot be detected from one half-hourly map to the next, but there is a general transference of the rain-pattern in a south-easterly direction.

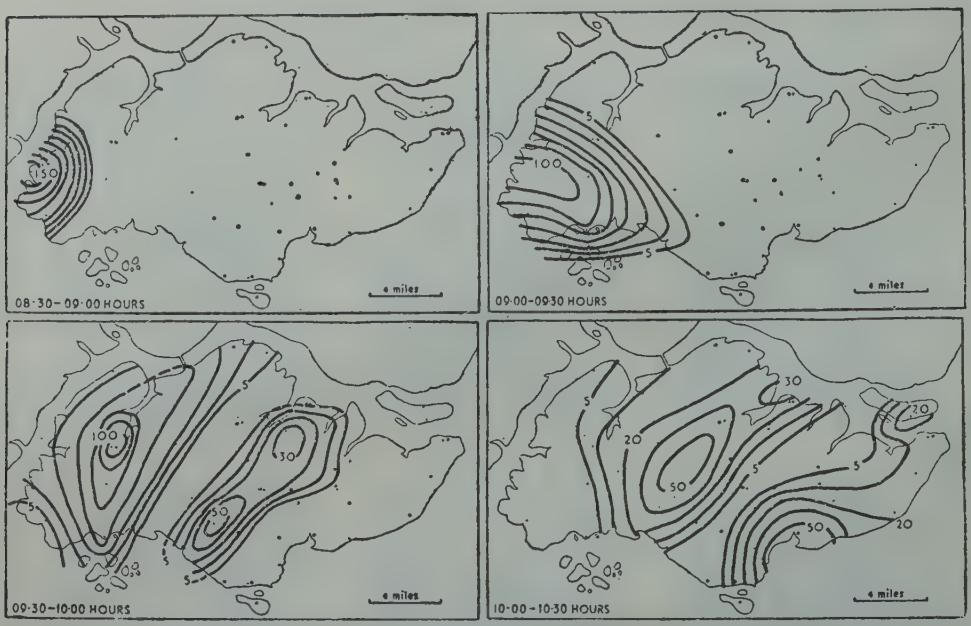

Fig. 34. Singapore: half-hourly isohyets for 5/8/53. A sumatra consisting of two eastward-moving rain-bands. There was no change in the upper-winds (see Fig. 35).

The three cases examined indicate that there are numerous well-developed storms along or in the neighbourhood of an air-stream boundary, and not a line of cumulonimbus as at a cold front of temperate latitudes.

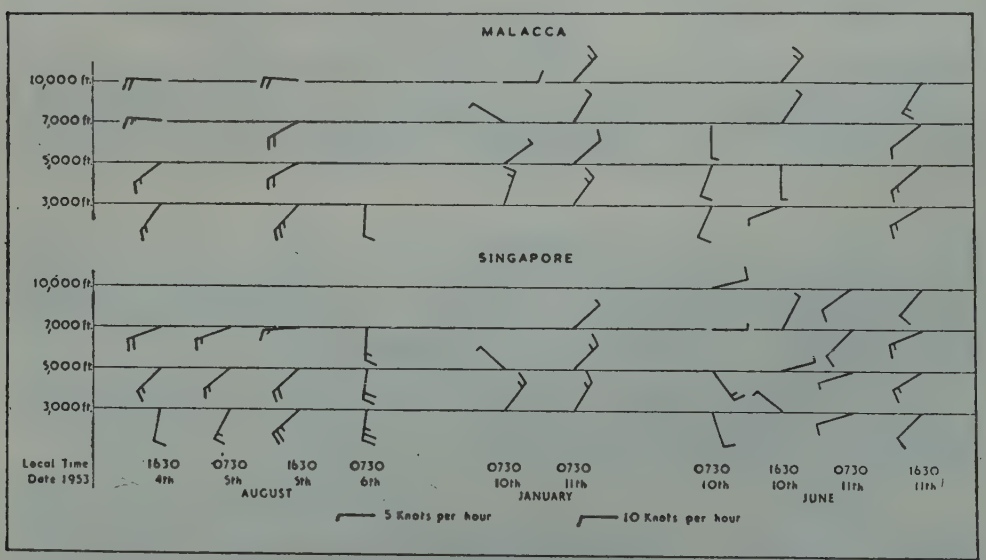

Fig. 35. Upper-winds at Malacca and Singapore. A short feather on an arrow denotes a wind speed of 5 knots, a long one of 10 knots.

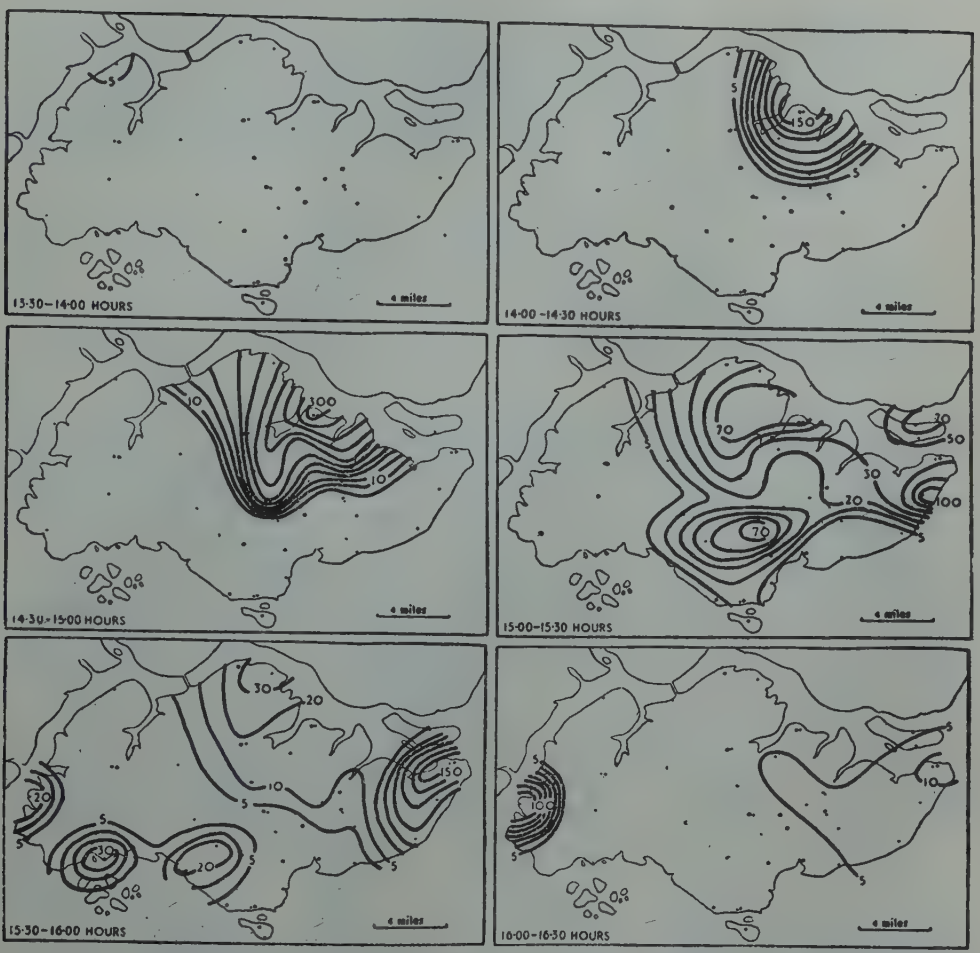

Fig. 36. Singapore: half-hourly isohyets for 10/6/53. An example of rainfall at the passage of an air-stream boundary (see upper-winds of Fig. 35), intensified locally by diurnal cumuliform development. The rainfall pattern accompanying the boundary was broken but contained at least one very intense centre.

(4) SUMATRAS

It was seen earlier how rain-bands crossed Singapore on 5/8/53 (Fig. 34) with no change in the upper south-westerly flow (Fig. 35). This is an example of a storm known locally as a *sumatra.* Sumatras occur wholly within the South-East Trades with little change of upper wind, and their structure is found to vary from lines of rain (as occurred on 5/8/53) to a zone of scattered storms (as on 30/8/53 and 2/9/53; Figs. 28 and 37). The selected maps showing the passage of sumatras may be interpreted as follows:—

(i) 5/8/53, 08.30-10.30 hours L.T. (Fig. 34).

Two rain-bands moved to the east or south-east, and their travel is proved by the times of onset of rain: Lim Chu Kang, 08.30 hours L.T; Pasir Laba, 08.30 hours; Tuas, 08.40 hours; Tanjong Kling, 09.00 hours; Jurong, 09.00 hours; and Woodlands, 09.45 hours L.T. Thomson Road had one light shower at 10.00 hours L.T. and another at 11.45 hours. MacRitchie had

one light shower at 09.45 hours and another at 11.00 hours L.T. Holland Road had rain at 09.40 hours and a light shower at 11.15 hours. Bukit Timah had only one heavy fall, starting at 10.00 hours L.T., which must have been associated with the storm moving from the west. It appears therefore that the two rain-bands shown for 09.30-10.00 hours L.T. are the same two shown for 10.00-10.30 hours. The edge of the rain-belt travelled eleven miles in three hours.

There was little change in upper-winds with the passage (Fig. 35). Kallang surface-wind changed at 10.10 hours L.T. from SSE 5 m.p.h. to SW 23 m.p.h., with gusts to 33 m.p.h., while Fullerton Building surface-wind changed at 09.55 hours L.T. from light and variable to N 20 m.p.h., with gusts to 37 m.p.h. Both these squalls occurred before the commencement of rain at the stations.

(ii) 30/8/55, 22.30 hours L.T. — 31/8/53, 00.30 hours L.T. (Fig. 28).

The early morning storm at Thomson Road moved four miles southward in less than one hour. The dearth of rain at Kallang and late arrival at Paya Lebar Police Station shows that the Bedok storm was a separate entity which

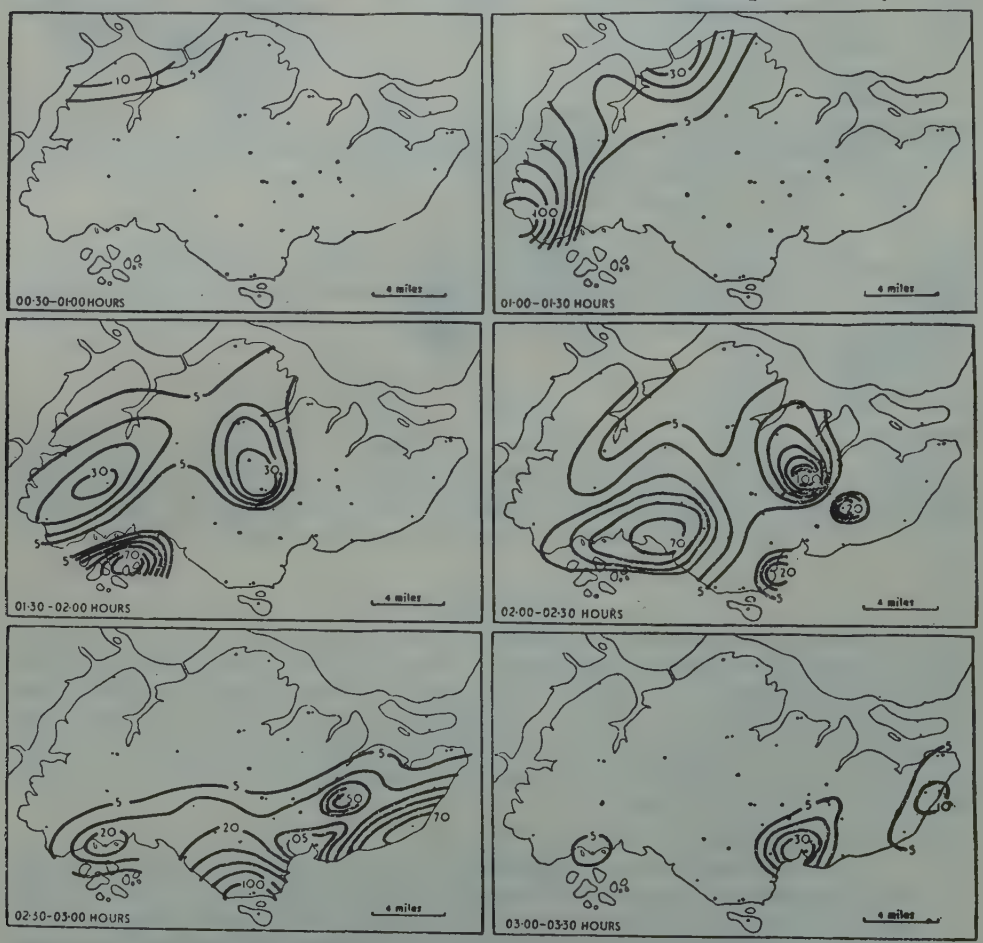

Fig. 37. Singapore: half-hourly isohyets for 2/9/53. A sumatra consisting of separate intense storms and with no change in upper winds.

later travelled six miles to the west-north-west in less than one hour. This movement can be seen from the times of onset of rain: Joo Chiat, 23.00 hours L.T; Jalan Eunos, 23.00 hours; P.W.D. Paya Lebar, 23.15 hours; and Paya Lebar Police Station, 23.30 hours. The total life of each storm was 1-1½ hours with a long period of general rain later.

Upper-winds at Kallang at 07.30 hours L.T. on the 31st were:

3000 ft.	270°/43	knots
5000 „	250°/23	„
7000 „	250°/26	„

Kallang had a strong squall at 23.00 hours L.T. when the wind changed from light and variable to westerly 25 m.p.h., with gusts to 37 m.p.h. The storm was then close to Kallang but rain had not commenced.

(iii) 2/9/53, 00.30-03.30 hours L.T. (Fig. 37).

In this case there was a general transference of precipitation eastwards, but the separate centres were individually of short life and little movement. The Pulau Seraya storm was not the same as that at Tuas, since there was no rain at Tanjong Kling before 02.00 hours L.T. The Pulau Seraya storm moved three miles to the east-north-east in less than one hour. The Mac-Ritchie storm moved four miles east-north-eastward to Paya Lebar in less than one hour. The storm at Paya Lebar probably induced the other at Jalan Eunos two miles to the south-east, and it was the latter storm which spread to the east coast. Although the large storm in the south never reached Kallang, a squall of twenty minutes' duration commenced there at 02.30 hours L.T., when the wind turned from light and variable to SW 20 m.p.h., with gusts to 36 m.p.h. Fullerton Building also had a squall at 02.15 hours L.T., just before the rain commenced; the wind turned from SSW 5 m.p.h. to NW 22 with gusts to 37 m.p.h.

Upper winds at Kallang at 16.30 hours L.T. were:

3000 ft.	220°/07	knots
5000 „	250°/13	„
7000 „	290°/32	„

The three examples described above show that the structure of sumatras may vary from an eastward moving belt of rain to a series of separate, large, short-lived storms. In the latter instances, a new storm usually (but not necessarily) forms down-wind from a dying storm (with reference to the wind at 5000-7000 ft.). The features common to all sumatras are:

(i) They occur mainly in the months May to September, though sometimes as early as March or as late as November[1].

(ii) They occur mostly in the night or early morning[2].

(iii) They are accompanied by strong cold squalls. The examples described herein show that the squall occurs close to the eastward side of the rainfall pattern of each storm, supporting Sawyer's[3] suggestion that the squall is a cold down-draft consisting of air which has originated in the top of a cumulonimbus and been carried eastwards with the upper wind.

1. I.E.M. Watts, "Line-Squalls of Malaya", *The Malayan Journal of Tropical Geography*, Vol. 3 (Singapore, 1954), pp. 1-14.
2. .Ibid.
3. J.S. Sawyer, "Cooling of Air by Rain as a Factor in Convection" *Meteorological Office Professional Note No. 96* (London, 1949), pp. 1-11.

CHAPTER VIII

SOME IMPLICATIONS

Despite the high annual rainfall and a seasonal variation so small that plant growth is practically continuous, insufficient water is collected on the Island of Singapore to meet the needs of the inhabitants. In many other regions where the annual rainfall is as great as that of Singapore, periods of rain lasting several hours or days may interrupt certain operations such as civil aviation. As the individual storms over Singapore are of short life, such interruptions are rare here. These aspects are discussed below.

(1) WATER CATCHMENT

The total amount of water piped to consumers during 1952 was 14,033 million gallons[1]. The main loss from stored water is due to evaporation and the average evaporation at Singapore is shown in Table 14.

TABLE 14: MONTHLY AND ANNUAL EVAPORATION AT SINGAPORE (IN INCHES)

J	F	M	A	M	J	J	A	S	O	N	D	YEAR
4.91	4.92	5.77	5.47	5.43	5.65	5.53	5.51	5.44	5.51	4.70	4.93	63.77

This Table has been prepared from the average monthly values obtained with three-inch evaporimeters at MacRitchie, Pierce and Seletar Reservoirs during 1947-53. The normal loss can be estimated[2] at 50 per cent of the rainfall, so that the required annual catch is 28,066 million gallons.

The total catchment area necessary to meet the annual consumption plus loss is shown in Table 15. This has been calculated on the basis of precipitation average (see Chapter III), on extreme maximum and on extreme minimum annual rainfall. It shows that, although a catchment area of 7,610 acres would collect sufficient water to meet demands in the wettest year, over 16,000 acres would be required in the driest year.

TABLE 15: CATCHMENT AREA REQUIRED TO COLLECT 28,066 MILLION GALLONS PER YEAR

ANNUAL RAINFALL (INCHES)		CATCHMENT AREA (ACRES)
MEAN (PRECIPITATION AVERAGE, PAGE....ABOVE)	97·14	10,640
EXTREME MAX. (GOVT. RECORDS 84 YRS., FIG. 3)	135·92	7,610
EXTREME MIN. (GOVT. RECORDS 84 YRS., FIG. 3)	63·21	16,360

1. W.S. Stredwick, *Annual Report of the City Council of Singapore Water Dept. for* 1952 (Singapore, 1953).
2. Ibid.

The present total catchment area of MacRitchie, Pierce and Seletar Reservoirs is 7,573 acres (1,890, 3,007 and 2,676 acres respectively), which is inadequate for even the wettest years. To collect sufficient water to meet all requirements the catchment area would need to be more than twice the present area[1]. Because this is not practicable owing to the density of population and the absence of natural features facilitating the impounding of water, the deficit has to be made up by leading water from Johore into the delivery mains.

(2) EFFECTS OF RAINFALL ON PLANT GROWTH

Owing to the high rainfall and its even monthly distribution, vegetation on the Island is abundant and the growth of most plants is practically continuous throughout the year. Another effect of the small seasonal variation of rainfall is that certain species have developed whose periodicity in growth and flowering is unrelated to the rainfall regime[2].

The rainfall is not regular enough, however, for vegetable cultivation, which requires sufficient soil-moisture at all times to allow the plants unimpaired intake. Blaut[3] states that, on some farms, hand-watering is undertaken at least once per day and even four times on sunny days during dry spells. On the other hand, root-drowning occurs after long periods of heavy rain or shorter intense rains. The choice of localities for vegetable-growing is not influenced by climatic variations, but depends on soil types and available sites. In general a clay is preferable to a lighter soil as, although the clay may be more difficult to work, it retains the water[4].

(3) EFFECT OF RAINSTORMS ON THE LANDING OF AIRCRAFT

It was shown in Chapter VI (4) that discrete storms over Singapore rarely last more than two hours and that the longest duration of a storm in 1953 was not more than six hours. The composite storms of Chapter VII showed a similarly short life.

The short duration of storms contributes greatly to the safety of aircraft operation. Even accepting that the movement of individual storm-centres is slight [Chapter VI (3)], it is apparent that few of the storms would prohibit landings at aerodromes for periods greater than two hours, and most long-range aircraft are able to 'hold' this long if it is certain that there will be no necessity to proceed to alternative landing-fields.

The short duration of storms is reflected in the visibility and cloud-base at a single station. Table 16 shows the number of occurrences during two years (January 1950-December 1951) when there were restrictive conditions of low cloud and poor visibility at Kallang Airport.

1. In July, 1955 the three reservoirs were collecting only 30 per cent of the amount consumed.
2. R.E. Holttum, "Evolutionary Trends in an Equatorial Climate," *Symposia of the Society of Experimental Biology, No. 7* (1953), p. 173.
3. J.M. Blaut, "The Economic Geography of a One-acre Farm on Singapore Island," *The Malayan Journal of Tropical Geography,* Vol. 1 (1953) p. 41.
4. Ibid, p. 44.

TABLE 16: NUMBER OF OCCASIONS WHEN CLOUD-BASE (FOR AMOUNTS > 4/8) AT KALLANG WAS 1,000 FT. OR LOWER AND/OR VISIBILITY WAS 2 MILES OR LESS (1950-1)

WEATHER MINIMA REPORTED	NO. OF OCCASIONS
AT 1 HOURLY OBSERVATIONS	109
,, 2 CONSECUTIVE HOURLY OBSERVATIONS	28
,, 3 ,, ,, ,,	8
,, 4 ,, ,, ,,	5
,, 5 ,, ,, ,,	3
,, 6 ,, ,, ,,	1

Observations were made every hour during this period and the limits of cloud-base of 1,000 ft. or lower and visibility two miles or less have been chosen in accordance with international procedure. Nearly all the occasions listed in Table 16 should refer to storms because (i) radiation fog is not common at Kallang and it rarely reduces visibility for as long as one hour, and (ii) the convective condensation level is usually from 2000 to 3000 ft., so that cloud-bases lower than this are mostly due to heavy rain.

Table 16 shows that, out of 154 occurrences of restrictive conditions, only seventeen lasted two hours or more, and there was only one occasion when the conditions persisted for as long as five hours. Thus Table 16 bears a close resemblance to Table 13 which lists the frequency during 1953 of storms lasting longer than one hour.

Analysis shows that the seventeen occasions of restrictive conditions lasting two hours or more during 1950-51 (Table 16) occurred at various times of day, while most landings at Kallang were during the late afternoon. Therefore there was slight chance that the conditions would interfere with aircraft landing. In confirmation of this, records of the Department of Civil Aviation show that there were only two occasions during those two years when aircraft had to be diverted from Kallang, and it is not certain that these diversions were made solely because of bad weather.

CHAPTER IX

CONCLUSIONS

(1) SUMMARY

(i) Using long-period rainfall records, monthly and annual 'precipitation averages' have been established for central and southern portions of the Island of Singapore. The seasonal variation there is shown to be related to the upper wind.

(ii) Except in May, June, July and December, mean rainfall each month is higher in the north than elsewhere. Mean annual rainfall varies from 83 in. in the south to at least 115 in. in the north. The monthly isohyetal patterns of a close network of gauges during 1953 approximately accord with these findings, but there can be large variations in the horizontal gradient of total rainfall in any month.

(iii) From December to March rain occurs most frequently between 15.00 and 16.00 hours, with a secondary maximum at about 06.00 hours in December and January. After April the afternoon maximum decreases in prominence and a morning maximum increases until in September and October most precipitation occurs between 06.00 and 08.00 hours. After November the morning peak of frequencies decreases. In any one month the diurnal variation does not differ greatly across the Island and the diurnal variation of rainfall over the neighbouring sea is similar to that over central Singapore.

(iv) Isohyetal patterns associated with separate storms are mostly circular and less than six miles in diameter but sometimes as wide as eleven miles. Few storms have rainfall lasting longer than one hour, and very few last more than two hours. The movement of individual storm-centres is small and unrelated to the upper-winds.

Owing to the small horizontal extent of individual storms, the falls recorded by a gauge during a particular day or month differ greatly in some cases from those of a neighbouring gauge. Rain-days per month as recorded by a single gauge are similarly unrepresentative. Five gauges distributed over the Island are required for a definition of monthly rain-days.

(v) There are periods of general rain over Singapore, some of which are associated with the boundary between two air-streams. At an air-stream boundary there are numerous intense separate or merging storms but not necessarily a continuous line of precipitation. The rainfall-patterns associated with sumatras vary from continuous rain-bands to separate storms.

(2) PROBLEMS REQUIRING FURTHER EXAMINATION

In certain respects this investigation is incomplete. For instance, the mean monthly and annual isohyetal patterns have not been extended to the west of the Island owing to lack of data, while isohyets for its northern areas have been drawn on inadequate bases. A good permanent network has been established since the beginning of 1954 with the view that reliable mean monthly and annual isohyets might be constructed at the end of a decade.

It has been accepted throughout the study that placing a gauge on a high building does not thereby lessen the catch. As there is a difference of opinion in this respect, a separate investigation has been started[1].

In the study of moving isohyetal patterns, storms of very small horizontal extent have necessarily been neglected owing to the coarseness of the network of recording rain-gauges (one per six sq. miles). To study these smaller storms, a denser network (one per two sq. miles) has been established over the City during 1954. It is possible that isohyets for periods of less than half an hour may be drawn with the new network, since the accessibility of the instruments ensures that their timing can be checked frequently.

The study of diurnal variation of rainfall over the neighbouring sea has been started by establishing permanent gauges at Horsburgh, Raffles and Sultan Shoal Lighthouses. This is outside the scope of the present investigation.

1. The results of this investigation will be published in this *Journal* in 1957.

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